3.5.1.3 Normal Conditions of Transport Results – Model AOS-165

Table 3-64 lists the tables and figures in this appendix that present the Model AOS-165 transport package results under Normal conditions of transport, for Load Cases 101 through 106. Each table provides a list of temperatures at each monitoring node. Also listed are the maximum temperatures within each transport package component.

Table 3-65 lists the temperature monitoring points (nodes) for the Model AOS-165 transport package, under Normal and Hypothetical Accident (Fire) conditions of transport. Figure 3-79 illustrates the location of each node on the transport package, under Normal conditions.

Table 3-64. Normal Conditions of Transport Results – Model AOS-165

Load Case	Description	Results Table	Entire Model	Cask Model
101	100°F Ambient, Maximum Decay Heat	Table 3-66	Figure 3-80	Figure 3-81
102	100°F Ambient, Maximum Decay Heat, Maximum Insolation	Table 3-67	Figure 3-82	Figure 3-83
103	-20°F Ambient, Zero Decay Heat, Zero Insolation	Table 3-68	Figure 3-84	–
104	-40°F Ambient, Zero Decay Heat, Zero Insolation	Table 3-69	Figure 3-85	–
105	-40°F Ambient, Maximum Decay Heat	Table 3-70	Figure 3-86	Figure 3-87
106	-20°F Ambient, Maximum Decay Heat	Table 3-71	Figure 3-88	Figure 3-89

Table 3-65. Temperature Monitoring Points, All Conditions of Transport – Model AOS-165

Nodal Location	LIBRA Model Nodal Number	
	Normal Conditions	Fire Conditions
1	5001	5001
2	4532	4532
3	4227	4227
4	4752	4752
5	4838	4838
6	4995	4995
7	3309	3309
8	3419	3419
9	678	678
10	2537	2537
11	1888	1888
12	583	583
13	3001	3001
14	3148	3148
15	7533	7533
16	7377	7377
17	7371	7371
18	6942	6942
19	6267	6267
20	6121	6121
21	6001	6001
22	9501	15481
23	9950	16630
24	10014	16694
25	10781	18111
26	9091	1153
27	8463	9785
28	8462	9571
29	8197	8197
30	9711	15451
31	9821	15961
32	10158	17032
33	10605	17743
34	9102	11051
35	8578	9900
36	8225	8673
37	8001	8225

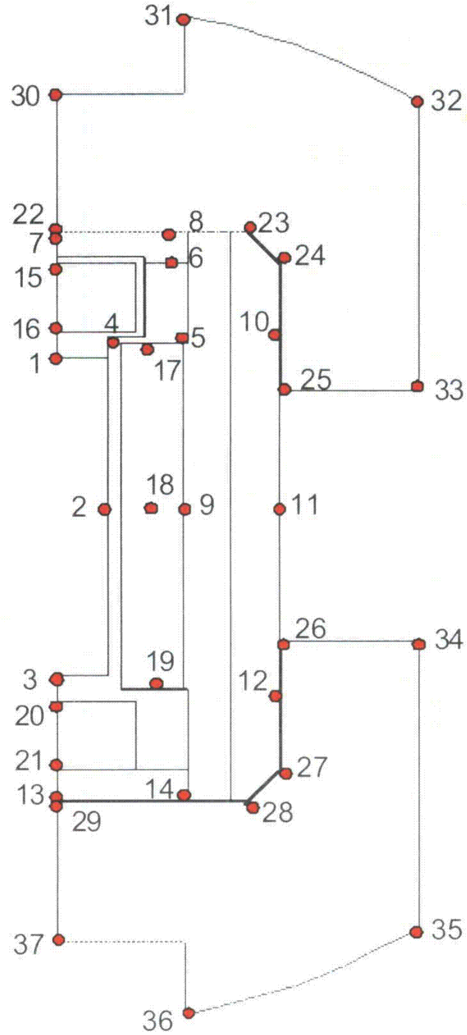

Figure 3-79. Selected Nodal Locations for Normal Conditions of Transport – Model AOS-165

Table 3-66. Load Case 101 – 100°F Ambient, Maximum Decay Heat – Model AOS-165

Location	Node	Temp(C)	Temp(F)
1	5001	358.78	677.80
2	4532	329.61	625.30
3	4227	344.78	652.60
4	4752	315.28	599.50
5	4838	283.89	543.00
6	4995	282.83	541.10
7	3309	290.11	554.20
8	3419	283.00	541.40
9	678	281.39	538.50
10	2537	267.72	513.90
11	1888	243.28	469.90
12	583	268.61	515.50
13	3001	287.89	550.20
14	3148	279.78	535.60
15	7533	301.67	575.00
16	7377	307.44	585.40
17	7371	292.50	558.50
18	6942	293.56	560.40
19	6267	292.39	558.30
20	6121	296.28	565.30
21	6001	291.33	556.40
22	9501	289.78	553.60
23	9950	273.78	524.80
24	10014	270.17	518.30
25	10781	168.44	335.20
26	9091	168.56	335.40
27	8463	270.33	518.60
28	8462	274.50	526.10
29	8197	287.56	549.60
30	9711	42.06	107.70
31	9821	38.50	101.30
32	10158	38.33	101.00
33	10605	39.61	103.30
34	9102	39.61	103.30
35	8578	38.33	101.00
36	8225	38.50	101.30
37	8001	42.06	107.70

Maximum Component Temperatures

Component	Node_1	Node_2	Node	Max_Temp(C)	Max_Temp(F)
Outside Shell	101	2894	606	2.8400E+02	5.4320E+02
Bottom Plate	3001	3232	3120	2.8917E+02	5.5250E+02
Lid	3233	3424	3233	2.9122E+02	5.5620E+02
Shell Cavity	4001	4998	4227	3.4478E+02	6.5260E+02
Plug	5001	5404	5001	3.5878E+02	6.7780E+02
Tungsten Alloy	6001	7656	7377	3.0744E+02	5.8540E+02
LAST-A-FOAM	8001	10791	9501	2.8978E+02	5.5360E+02

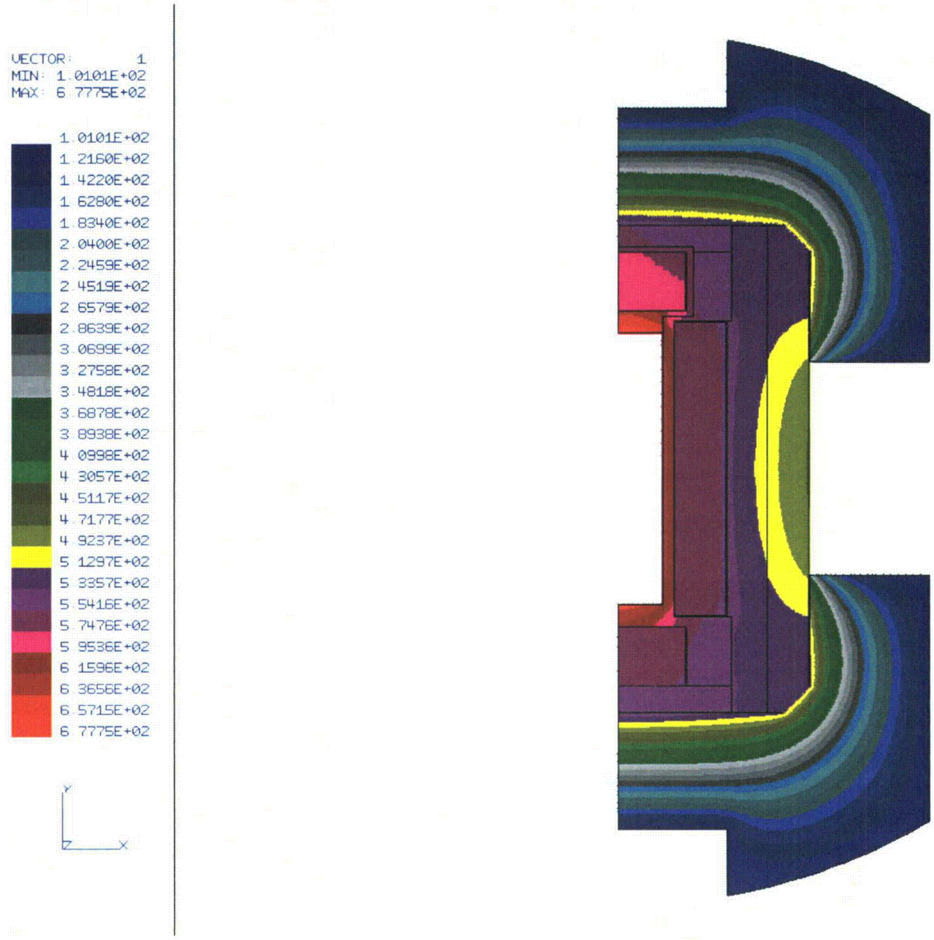

Figure 3-80. Load Case 101 – 100°F Ambient, Maximum Decay Heat, Entire Model – Model AOS-165

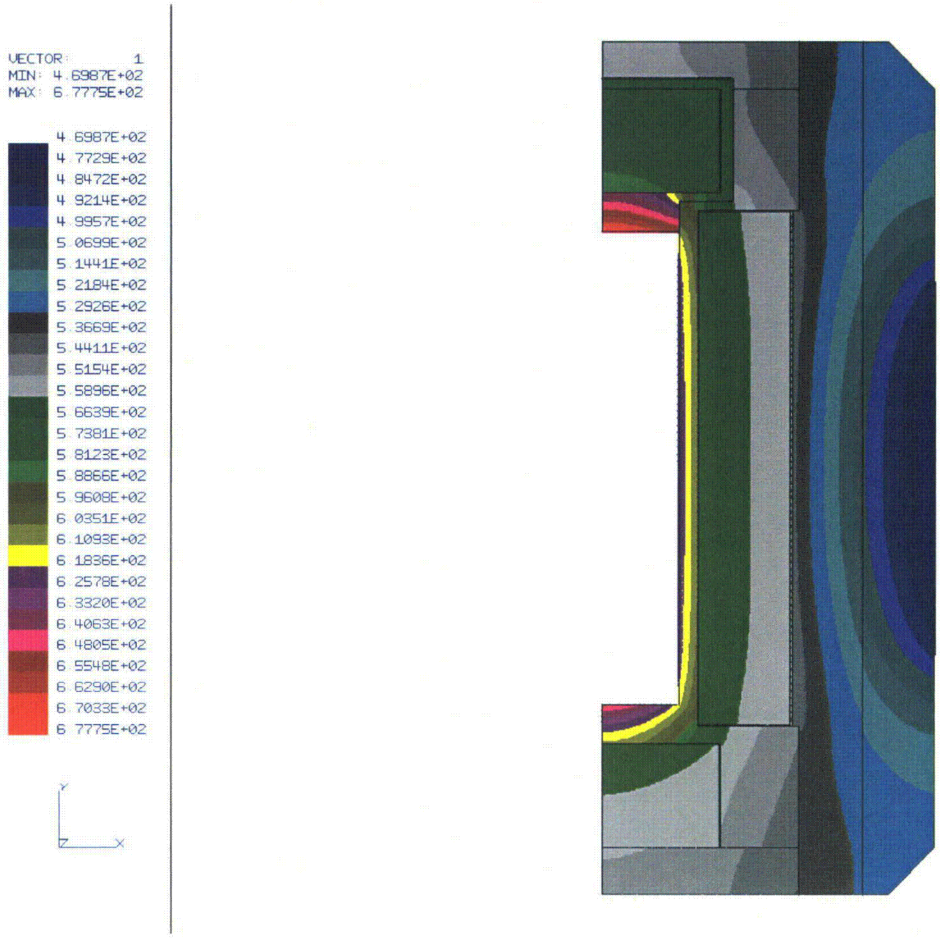

Figure 3-81. Load Case 101 – 100°F Ambient, Maximum Decay Heat, Cask Model – Model AOS-165

Table 3-67. Load Case 102 – 100°F Ambient, Maximum Decay Heat, Maximum Insolation – Model AOS-165

Location	Node	Temp(C)	Temp(F)
1	5001	379.22	714.60
2	4532	350.50	662.90
3	4227	365.67	690.20
4	4752	336.44	637.60
5	4838	305.44	581.80
6	4995	304.44	580.00
7	3309	311.56	592.80
8	3419	304.61	580.30
9	678	303.06	577.50
10	2537	289.44	553.00
11	1888	265.72	510.30
12	583	290.28	554.50
13	3001	309.39	588.90
14	3148	301.39	574.50
15	7533	322.72	612.90
16	7377	328.50	623.30
17	7371	314.06	597.30
18	6942	315.22	599.40
19	6267	313.94	597.10
20	6121	317.72	603.90
21	6001	312.83	595.10
22	9501	311.28	592.30
23	9950	295.61	564.10
24	10014	292.28	558.10
25	10781	189.50	373.10
26	9091	189.61	373.30
27	8463	292.44	558.40
28	8462	296.28	565.30
29	8197	309.11	588.40
30	9711	65.83	150.50
31	9821	80.22	176.40
32	10158	75.78	168.40
33	10605	68.39	155.10
34	9102	68.39	155.10
35	8578	75.78	168.40
36	8225	80.22	176.40
37	8001	65.83	150.50

Maximum Component Temperatures

Component	Node_1	Node_2	Node	Max_Temp(C)	Max_Temp(F)
Outside Shell	101	2894	606	3.0556E+02	5.8200E+02
Bottom Plate	3001	3232	3120	3.1067E+02	5.9120E+02
Lid	3233	3424	3233	3.1267E+02	5.9480E+02
Shell Cavity	4001	4998	4227	3.6567E+02	6.9020E+02
Plug	5001	5404	5001	3.7922E+02	7.1460E+02
Tungsten Alloy	6001	7656	7377	3.2850E+02	6.2330E+02
LAST-A-FOAM	8001	10791	9501	3.1128E+02	5.9230E+02

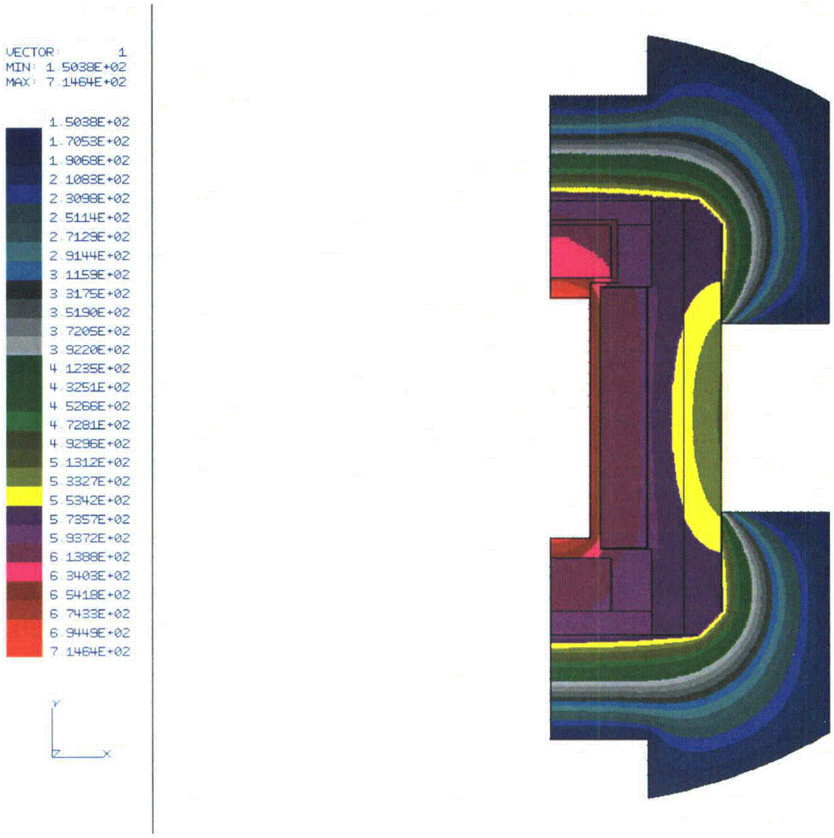

Figure 3-82. Load Case 102 – 100°F Ambient, Maximum Decay Heat, Maximum Insolation, Entire Model – Model AOS-165

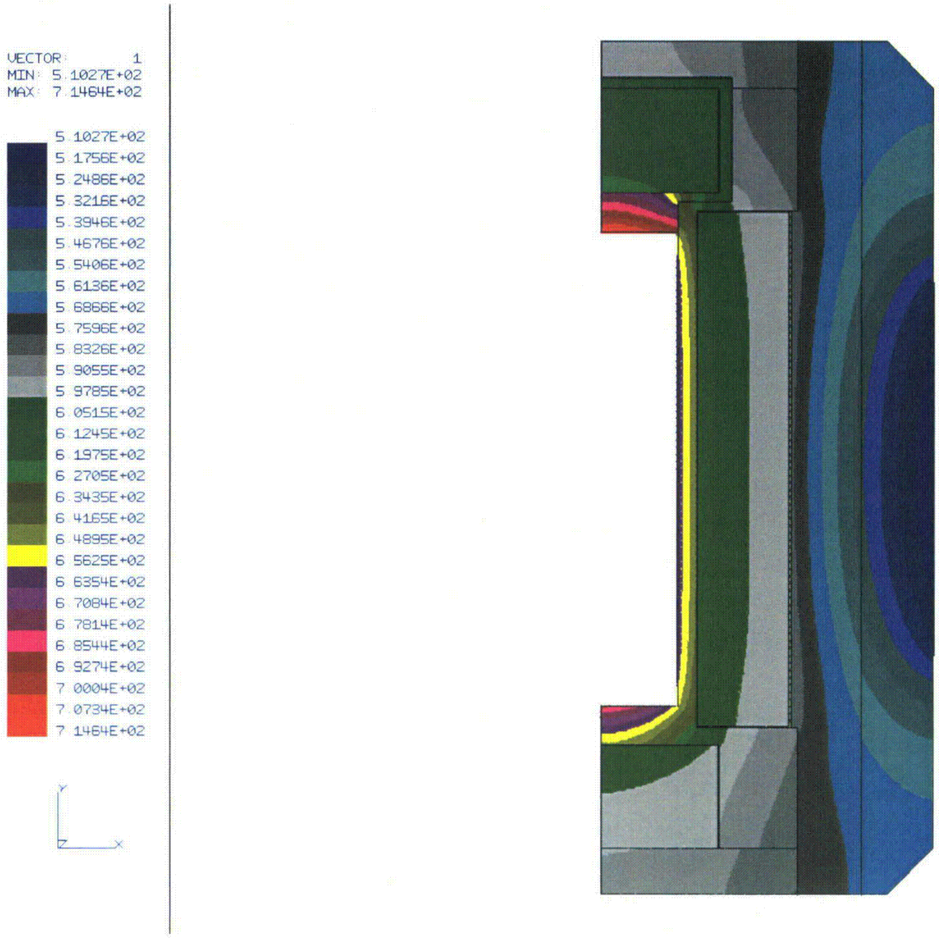

Figure 3-83. Load Case 102 – 100°F Ambient, Maximum Decay Heat, Maximum Insolation, Cask Model – Model AOS-165

Table 3-68. Load Case 103 – -20°F Ambient, Zero Decay Heat, Zero Insolation – Model AOS-165

Location	Node	Temp(C)	Temp(F)
1	5001	-28.89	-20.00
2	4532	-28.89	-20.00
3	4227	-28.89	-20.00
4	4752	-28.89	-20.00
5	4838	-28.89	-20.00
6	4995	-28.89	-20.00
7	3309	-28.89	-20.00
8	3419	-28.89	-20.00
9	678	-28.89	-20.00
10	2537	-28.89	-20.00
11	1888	-28.89	-20.00
12	583	-28.89	-20.00
13	3001	-28.89	-20.00
14	3148	-28.89	-20.00
15	7533	-28.89	-20.00
16	7377	-28.89	-20.00
17	7371	-28.89	-20.00
18	6942	-28.89	-20.00
19	6267	-28.89	-20.00
20	6121	-28.89	-20.00
21	6001	-28.89	-20.00
22	9501	-28.89	-20.00
23	9950	-28.89	-20.00
24	10014	-28.89	-20.00
25	10781	-28.89	-20.00
26	9091	-28.89	-20.00
27	8463	-28.89	-20.00
28	8462	-28.89	-20.00
29	8197	-28.89	-20.00
30	9711	-28.89	-20.00
31	9821	-28.89	-20.00
32	10158	-28.89	-20.00
33	10605	-28.89	-20.00
34	9102	-28.89	-20.00
35	8578	-28.89	-20.00
36	8225	-28.89	-20.00
37	8001	-28.89	-20.00

Maximum Component Temperatures

Component	Node_1	Node_2	Node	Max_Temp(C)	Max_Temp(F)
Outside Shell	101	2894	101	-2.8889E+01	-2.0000E+01
Bottom Plate	3001	3232	3001	-2.8889E+01	-2.0000E+01
Lid	3233	3424	3233	-2.8889E+01	-2.0000E+01
Shell Cavity	4001	4998	4001	-2.8889E+01	-2.0000E+01
Plug	5001	5404	5001	-2.8889E+01	-2.0000E+01
Tungsten Alloy	6001	7656	6001	-2.8889E+01	-2.0000E+01
LAST-A-FOAM	8001	10791	8001	-2.8889E+01	-2.0000E+01

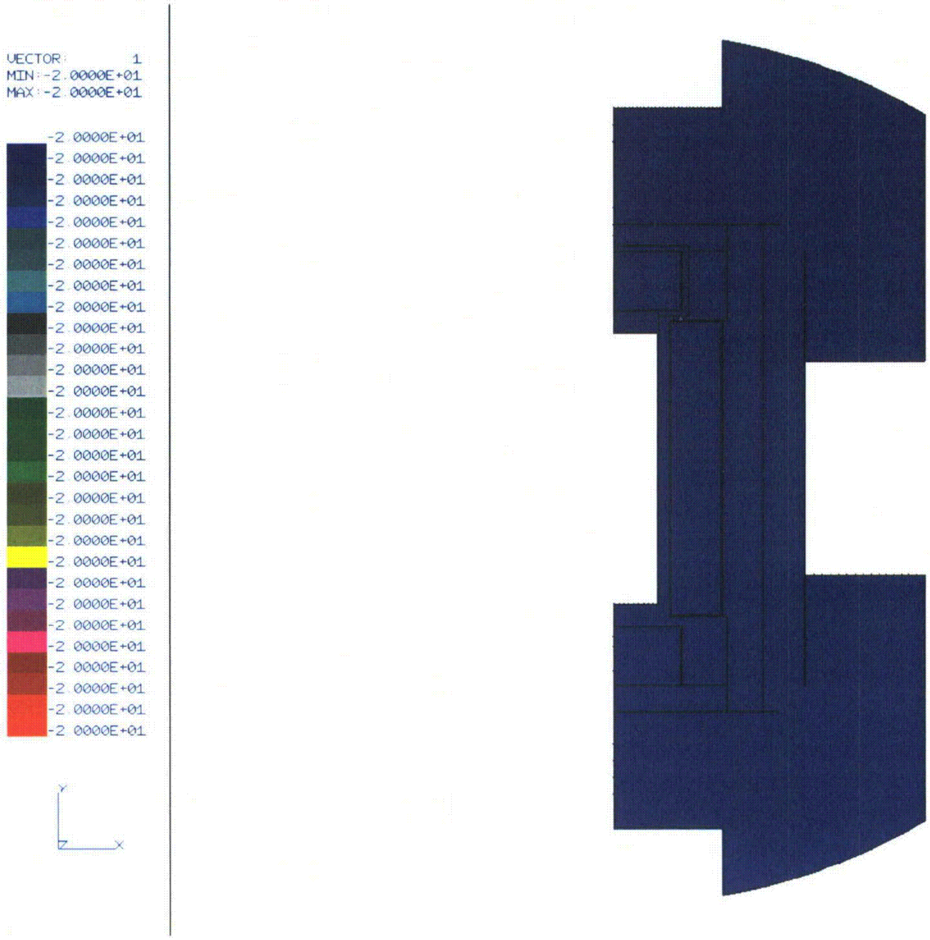

Figure 3-84. Load Case 103 – -20°F Ambient, Zero Decay Heat, Zero Insolation, Entire Model – Model AOS-165

Table 3-69. Load Case 104 – -40°F Ambient, Zero Decay Heat, Zero Insolation – Model AOS-165

Location	Node	Temp(C)	Temp(F)
1	5001	-40.00	-40.00
2	4532	-40.00	-40.00
3	4227	-40.00	-40.00
4	4752	-40.00	-40.00
5	4838	-40.00	-40.00
6	4995	-40.00	-40.00
7	3309	-40.00	-40.00
8	3419	-40.00	-40.00
9	678	-40.00	-40.00
10	2537	-40.00	-40.00
11	1888	-40.00	-40.00
12	583	-40.00	-40.00
13	3001	-40.00	-40.00
14	3148	-40.00	-40.00
15	7533	-40.00	-40.00
16	7377	-40.00	-40.00
17	7371	-40.00	-40.00
18	6942	-40.00	-40.00
19	6267	-40.00	-40.00
20	6121	-40.00	-40.00
21	6001	-40.00	-40.00
22	9501	-40.00	-40.00
23	9950	-40.00	-40.00
24	10014	-40.00	-40.00
25	10781	-40.00	-40.00
26	9091	-40.00	-40.00
27	8463	-40.00	-40.00
28	8462	-40.00	-40.00
29	8197	-40.00	-40.00
30	9711	-40.00	-40.00
31	9821	-40.00	-40.00
32	10158	-40.00	-40.00
33	10605	-40.00	-40.00
34	9102	-40.00	-40.00
35	8578	-40.00	-40.00
36	8225	-40.00	-40.00
37	8001	-40.00	-40.00

Maximum Component Temperatures

Component	Node_1	Node_2	Node	Max_Temp(C)	Max_Temp(F)
Outside Shell	101	2894	101	-4.0000E+01	-4.0000E+01
Bottom Plate	3001	3232	3001	-4.0000E+01	-4.0000E+01
Lid	3233	3424	3233	-4.0000E+01	-4.0000E+01
Shell Cavity	4001	4998	4001	-4.0000E+01	-4.0000E+01
Plug	5001	5404	5001	-4.0000E+01	-4.0000E+01
Tungsten Alloy	6001	7656	6001	-4.0000E+01	-4.0000E+01
LAST-A-FOAM	8001	10791	8001	-4.0000E+01	-4.0000E+01

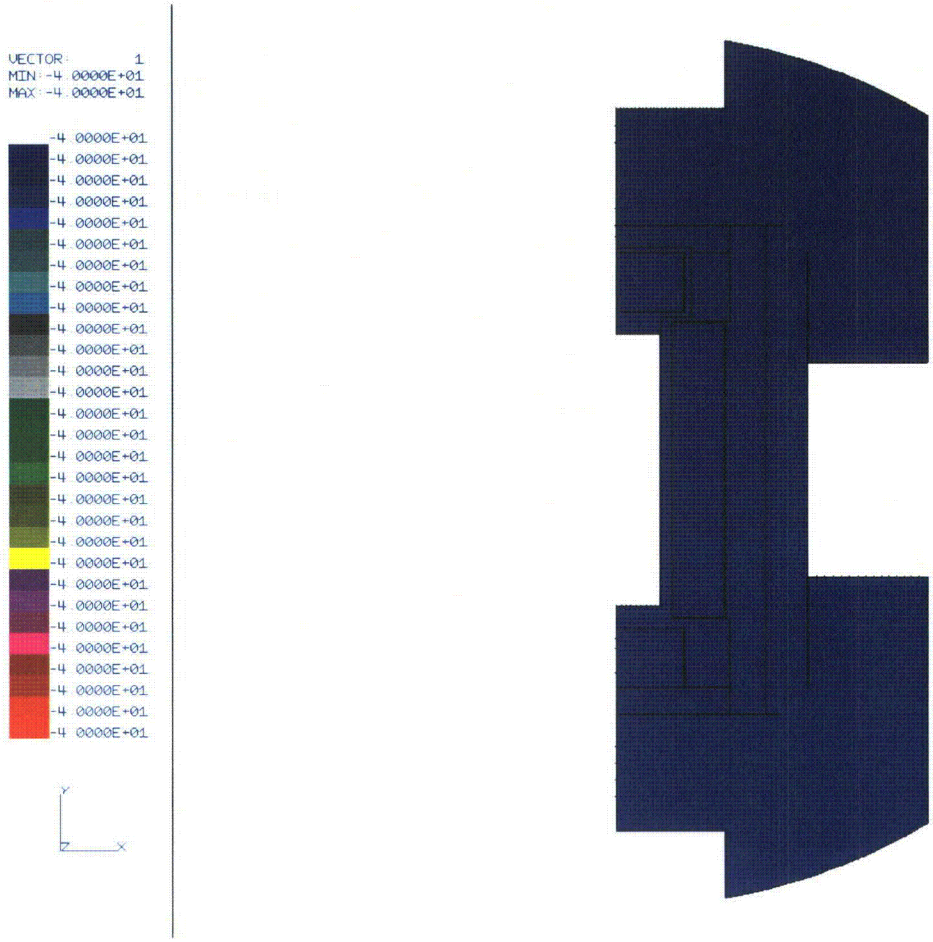

Figure 3-85. Load Case 104 – -40°F Ambient, Zero Decay Heat, Zero Insolation, Entire Model – Model AOS-165

Table 3-70. Load Case 105 – -40°F Ambient, Maximum Decay Heat – Model AOS-165

Location	Node	Temp(C)	Temp(F)
1	5001	292.44	558.40
2	4532	261.89	503.40
3	4227	277.11	530.80
4	4752	246.56	475.80
5	4838	213.56	416.40
6	4995	212.39	414.30
7	3309	220.17	428.30
8	3419	212.56	414.60
9	678	210.83	411.50
10	2537	196.50	385.70
11	1888	169.94	337.90
12	583	197.56	387.60
13	3001	217.83	424.10
14	3148	209.22	408.60
15	7533	233.17	451.70
16	7377	239.00	462.20
17	7371	222.17	431.90
18	6942	223.06	433.50
19	6267	222.00	431.60
20	6121	226.39	439.50
21	6001	221.28	430.30
22	9501	219.83	427.70
23	9950	202.67	396.80
24	10014	198.11	388.60
25	10781	89.06	192.30
26	9091	89.11	192.40
27	8463	198.28	388.90
28	8462	203.56	398.40
29	8197	217.50	423.50
30	9711	-35.51	-31.91
31	9821	-39.09	-38.36
32	10158	-39.38	-38.89
33	10605	-38.22	-36.79
34	9102	-38.22	-36.79
35	8578	-39.38	-38.89
36	8225	-39.09	-38.36
37	8001	-35.52	-31.94

Maximum Component Temperatures

Component	Node_1	Node_2	Node	Max_Temp(C)	Max_Temp(F)
Outside Shell	101	2894	606	2.1367E+02	4.1660E+02
Bottom Plate	3001	3232	3120	2.1917E+02	4.2650E+02
Lid	3233	3424	3233	2.2139E+02	4.3050E+02
Shell Cavity	4001	4998	4227	2.7711E+02	5.3080E+02
Plug	5001	5404	5001	2.9244E+02	5.5840E+02
Tungsten Alloy	6001	7656	7377	2.3900E+02	4.6220E+02
LAST-A-FOAM	8001	10791	9501	2.1983E+02	4.2770E+02

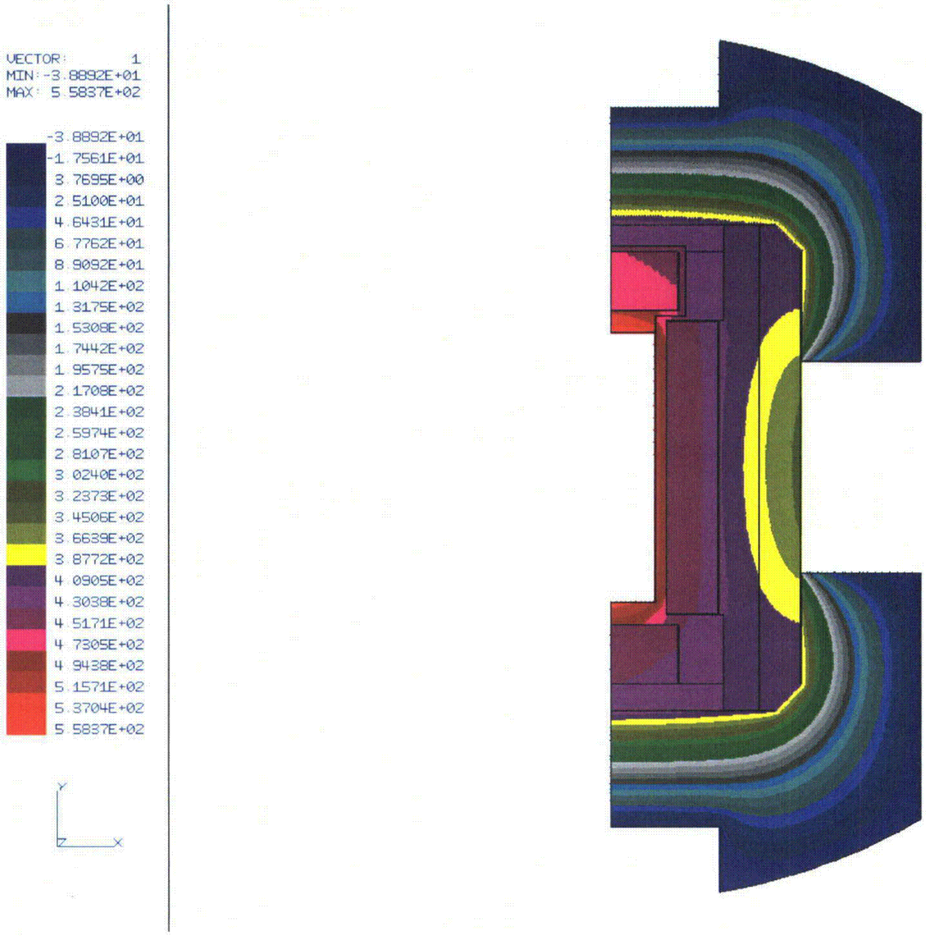

Figure 3-86. Load Case 105 – -40°F Ambient, Maximum Decay Heat, Entire Model – Model AOS-165

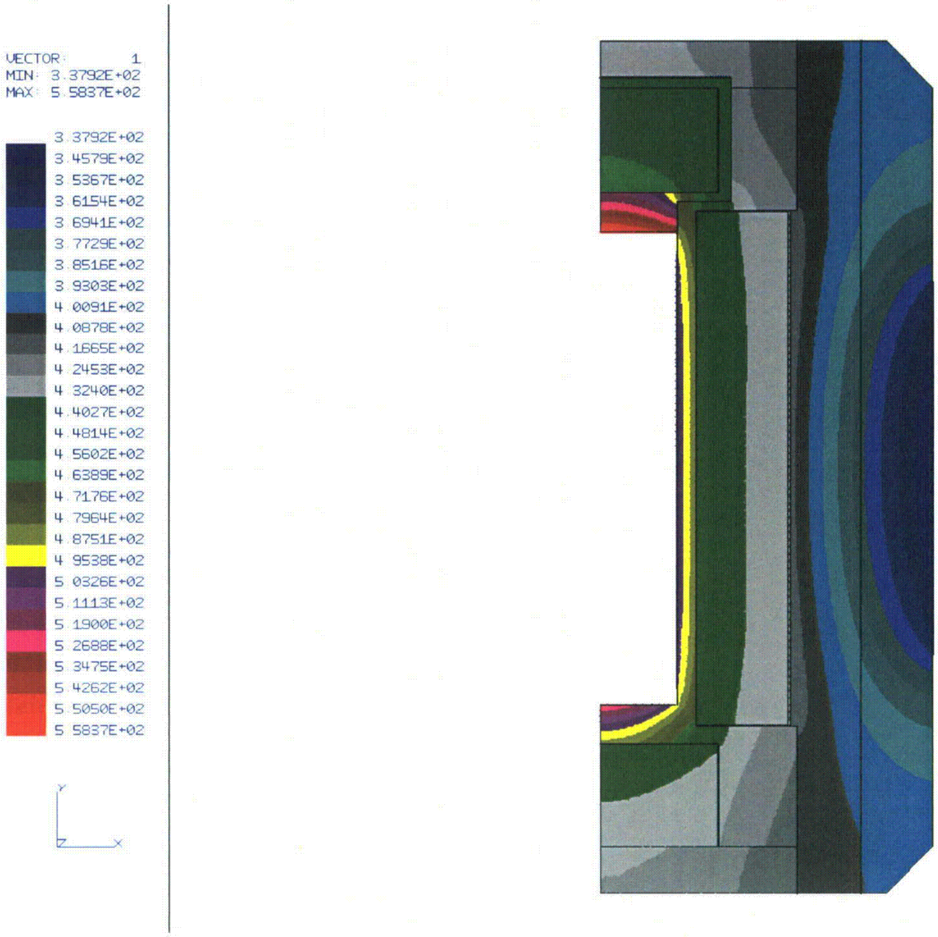

Figure 3-87. Load Case 105 – -40°F Ambient, Maximum Decay Heat, Cask Model – Model AOS-165

Table 3-71. Load Case 106 – -20°F Ambient, Maximum Decay Heat – Model AOS-165

Location	Node	Temp(C)	Temp(F)
1	5001	303.00	577.40
2	4532	272.72	522.90
3	4227	287.89	550.20
4	4752	257.56	495.60
5	4838	224.78	436.60
6	4995	223.61	434.50
7	3309	231.28	448.30
8	3419	223.78	434.80
9	678	222.11	431.80
10	2537	207.83	406.10
11	1888	181.67	359.00
12	583	208.89	408.00
13	3001	228.94	444.10
14	3148	220.44	428.80
15	7533	244.06	471.30
16	7377	249.94	481.90
17	7371	233.39	452.10
18	6942	234.33	453.80
19	6267	233.22	451.80
20	6121	237.50	459.50
21	6001	232.44	450.40
22	9501	230.94	447.70
23	9950	214.00	417.20
24	10014	209.61	409.30
25	10781	101.50	214.70
26	9091	101.61	214.90
27	8463	209.78	409.60
28	8462	214.89	418.80
29	8197	228.67	443.60
30	9711	-24.48	-12.06
31	9821	-27.97	-18.35
32	10158	-28.26	-18.86
33	10605	-27.08	-16.74
34	9102	-27.08	-16.74
35	8578	-28.26	-18.86
36	8225	-27.97	-18.35
37	8001	-24.49	-12.09

Maximum Component Temperatures

Component	Node_1	Node_2	Node	Max_Temp(C)	Max_Temp(F)
Outside Shell	101	2894	606	2.2489E+02	4.3680E+02
Bottom Plate	3001	3232	3120	2.3033E+02	4.4660E+02
Lid	3233	3424	3233	2.3250E+02	4.5050E+02
Shell Cavity	4001	4998	4227	2.8789E+02	5.5020E+02
Plug	5001	5404	5001	3.0300E+02	5.7740E+02
Tungsten Alloy	6001	7656	7377	2.4994E+02	4.8190E+02
LAST-A-FOAM	8001	10791	9501	2.3094E+02	4.4770E+02

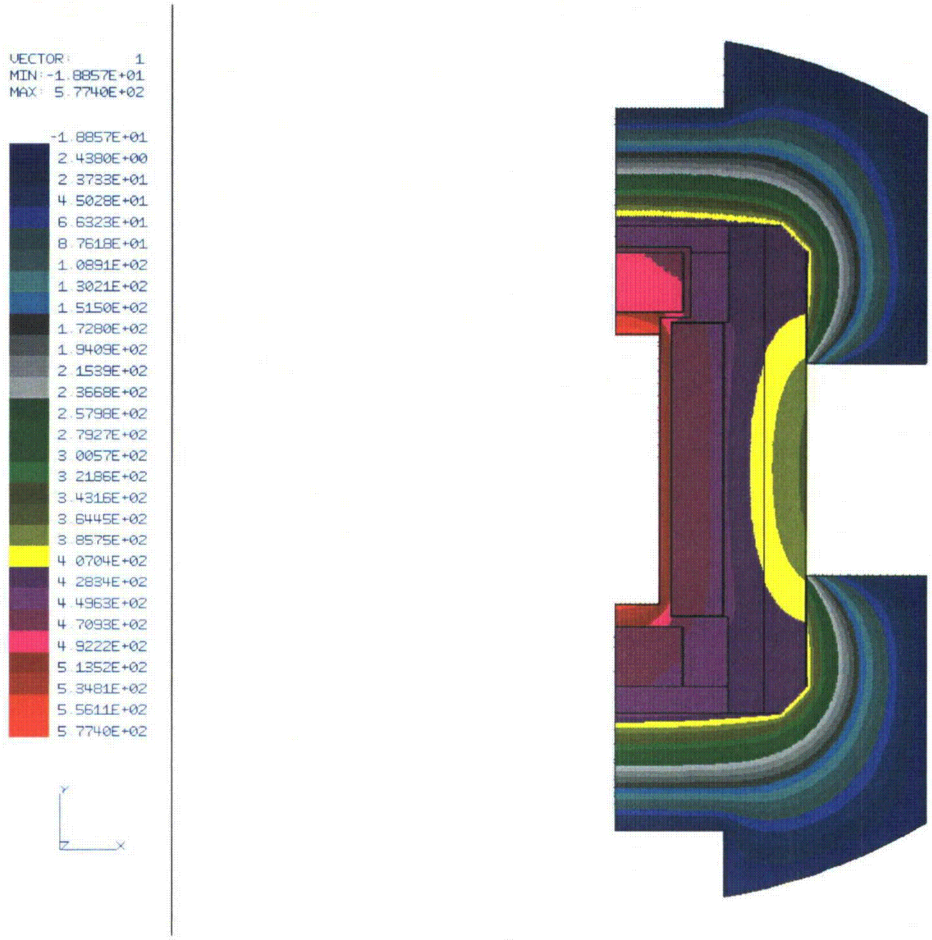

Figure 3-88. Load Case 106 – -20°F Ambient, Maximum Decay Heat, Entire Model – Model AOS-165

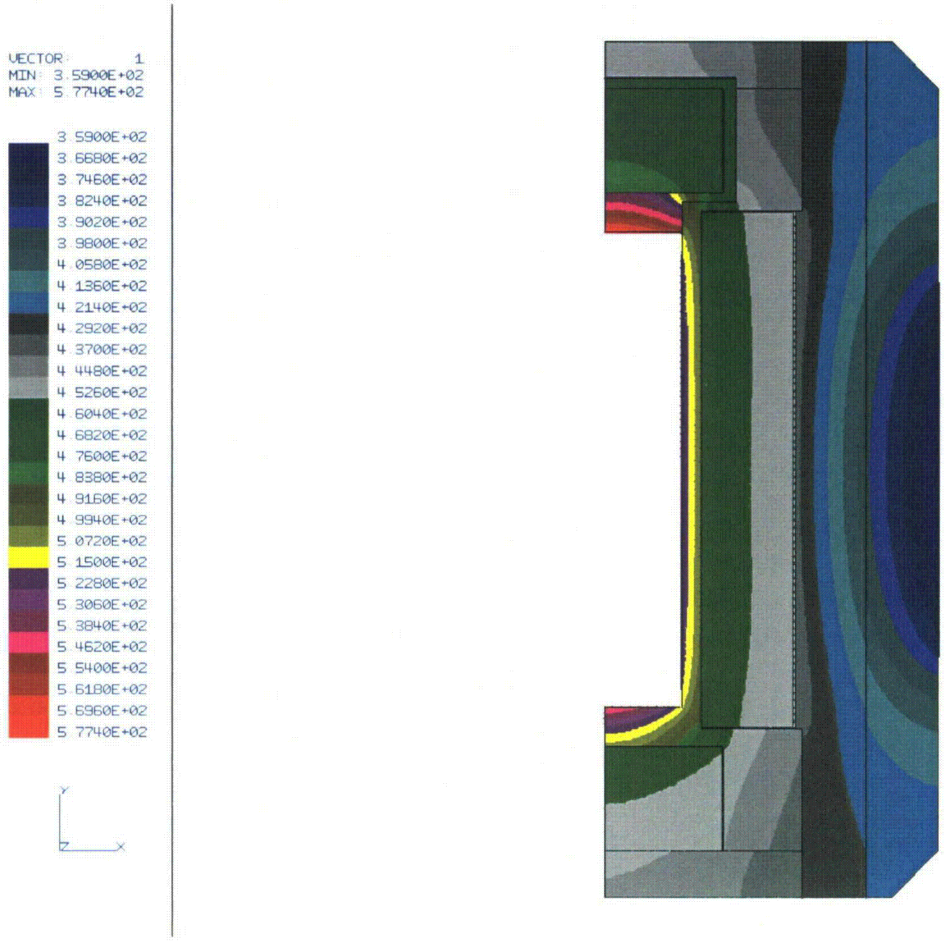

Figure 3-89. Load Case 106 – -20°F Ambient, Maximum Decay Heat, Cask Model – Model AOS-165

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3.5.2 Hypothetical Accident Conditions of Transport Results

This appendix presents the following:

- Hypothetical Accident Conditions of Transport Results – Model AOS-025
- Hypothetical Accident Conditions of Transport Results – Model AOS-050
- Hypothetical Accident Conditions of Transport Results – Model AOS-165

3.5.2.1 Hypothetical Accident Conditions of Transport Results – Model AOS-025

Table 3-72 lists the tables and figures in this appendix that present the Model AOS-025 transport package results under Hypothetical Accident conditions of transport, for Load Cases 111 through 116. Each table provides a list of temperatures at each monitoring node. Also listed are the maximum temperatures within each transport package component.

Table 3-73 lists the temperature monitoring points (nodes) for the Model AOS-025 transport package, under Normal and Hypothetical Accident (Fire) conditions of transport. Figure 3-90 illustrates the location of each node on the transport package, under Fire conditions.

Table 3-72. Hypothetical Accident Conditions of Transport Results – Model AOS-025

Load Case	Description	Results Table	Temperature versus Time	Entire Model	Cask Model
111	Fire at 30 Minutes, 1,475°F Ambient, Maximum Decay Heat	Table 3-74	Figure 3-91	Figure 3-92	Figure 3-93
112	Fire at 60 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation	Table 3-75	–	Figure 3-94	Figure 3-95
113	Fire at 90 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation	Table 3-76	–	Figure 3-96	Figure 3-97
114	Fire at 120 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation	Table 3-77	–	Figure 3-98	Figure 3-99
115	Fire at 150 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation	Table 3-78	–	Figure 3-100	Figure 3-101
116	Fire at 180 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation	Table 3-79	–	Figure 3-102	Figure 3-103

Table 3-73. Temperature Monitoring Points, All Conditions of Transport – Model AOS-025

Nodal Location	LIBRA Model Nodal Number	
	Normal Conditions	Fire Conditions
1	5001	5001
2	4532	4532
3	4227	4227
4	4752	4752
5	4838	4838
6	4995	4995
7	3309	3309
8	3419	3419
9	678	678
10	2537	2537
11	1888	1888
12	583	583
13	3001	3001
14	3148	3148
15	7533	7533
16	7377	7377
17	7371	7371
18	6942	6942
19	6267	6267
20	6121	6121
21	6001	6001
22	9501	11481
23	9950	12630
24	10014	12694
25	10781	13804
26	9091	10926
27	8463	9791
28	8462	9577
29	8197	8197
30	9711	11451
31	9821	11961
32	10158	13022
33	10605	13551
34	9102	10673
35	8578	9906
36	8225	8673
37	8001	8225

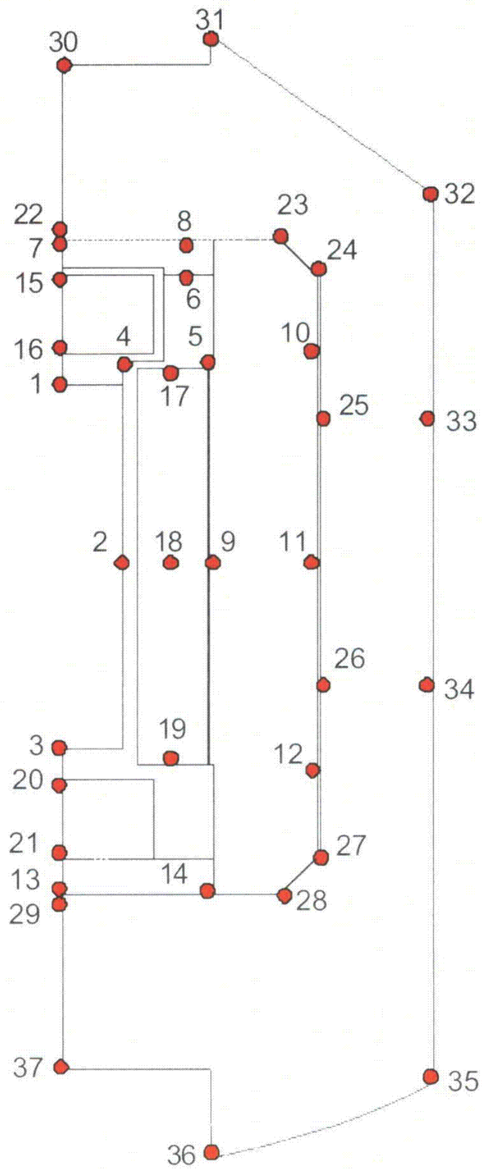

Figure 3-90. Selected Nodal Locations for Fire Conditions of Transport – Model AOS-025

Table 3-74. Load Case 111 – Fire at 30 Minutes, 1,475°F Ambient, Maximum Decay Heat – Model AOS-025

Location	Node	Temp(C)	Temp(F)
1	5001	112.22	234.00
2	4532	125.39	257.70
3	4227	121.61	250.90
4	4752	115.61	240.10
5	4838	113.39	236.10
6	4995	110.39	230.70
7	3309	106.39	223.50
8	3419	108.06	226.50
9	678	127.33	261.20
10	2537	115.33	239.60
11	1888	139.50	283.10
12	583	128.39	263.10
13	3001	114.28	237.70
14	3148	118.39	245.10
15	7533	108.22	226.80
16	7377	108.50	227.30
17	7371	119.94	247.90
18	6942	125.56	258.00
19	6267	126.17	259.10
20	6121	117.89	244.20
21	6001	117.44	243.40
22	11481	106.06	222.90
23	12630	111.67	233.00
24	12694	115.06	239.10
25	13804	135.44	275.80
26	10926	214.11	417.40
27	9791	130.17	266.30
28	9577	122.28	252.10
29	8197	113.50	236.30
30	11451	793.33	1460.00
31	11961	797.22	1467.00
32	13022	796.11	1465.00
33	13551	793.33	1460.00
34	10673	781.67	1439.00
35	9906	796.67	1466.00
36	8673	615.56	1140.00
37	8225	248.06	478.50

Maximum Component Temperatures

Component	Node_1	Node_2	Node	Max_Temp(C)	Max_Temp(F)
Outside Shell	101	2894	1767	1.4883E+02	2.9990E+02
Bottom Plate	3001	3232	3148	1.1839E+02	2.4510E+02
Lid	3233	3424	3360	1.0889E+02	2.2800E+02
Shell Cavity	4001	4998	4437	1.2656E+02	2.5980E+02
Plug	5001	5404	5012	1.1317E+02	2.3570E+02
Tungsten Alloy	6001	7656	6740	1.2739E+02	2.6130E+02
LAST-A-FOAM	8001	15086	11881	7.9722E+02	1.4670E+03

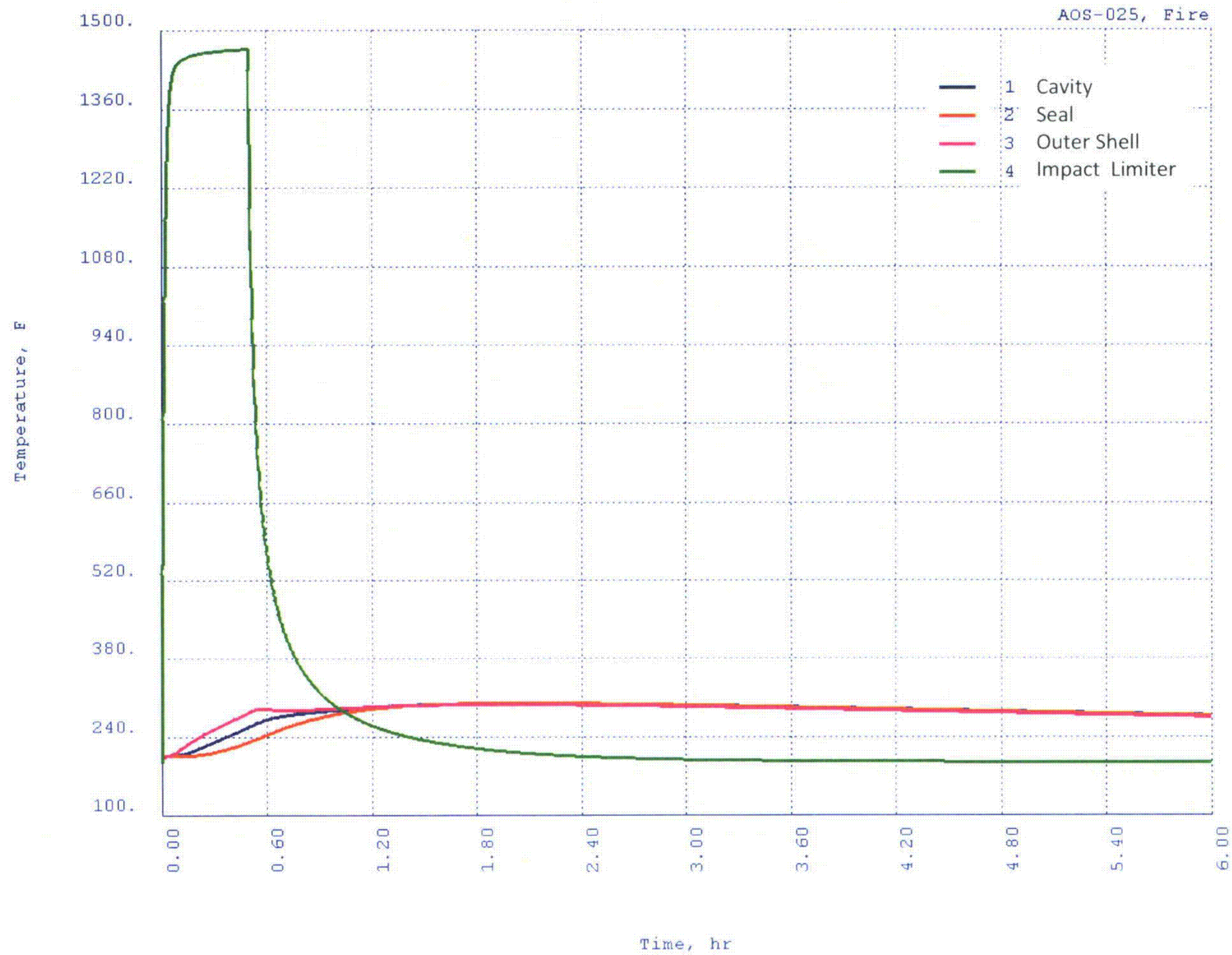

Figure 3-91. Load Case 111 – Fire at 30 Minutes, 1,475°F Ambient, Maximum Decay Heat, Temperature versus Time – Model AOS-025

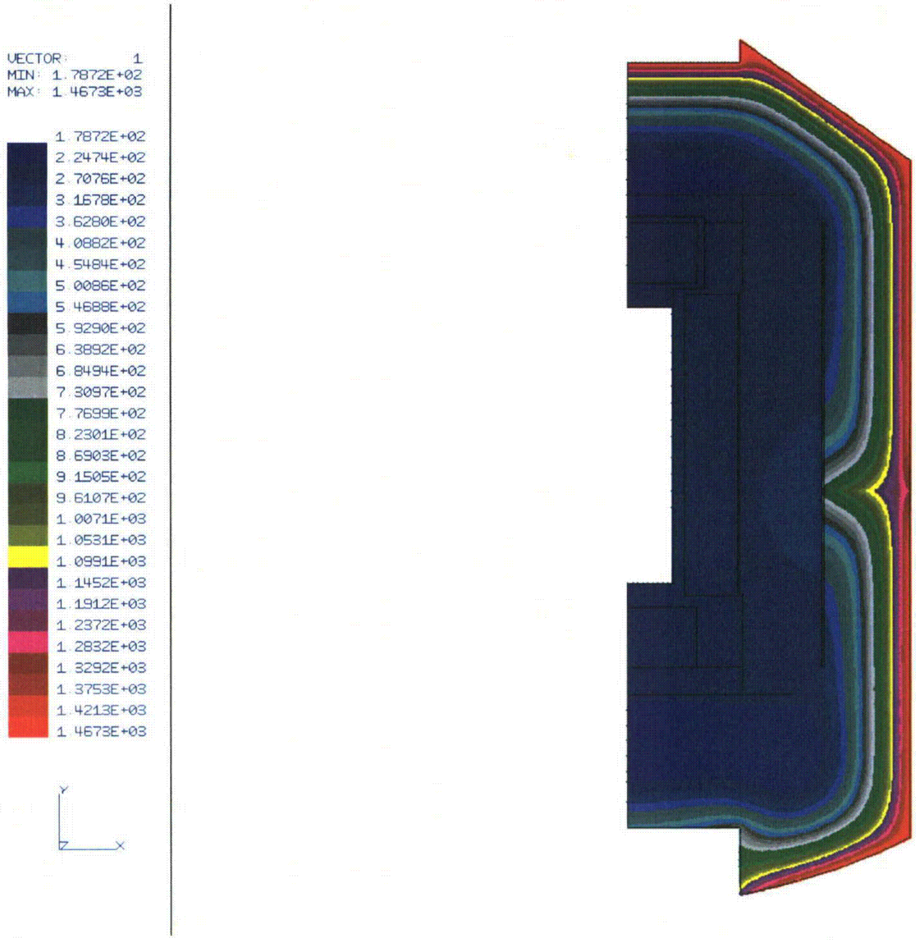

Figure 3-92. Load Case 111 – Fire at 30 Minutes, 1,475°F Ambient, Maximum Decay Heat, Entire Model – Model AOS-025

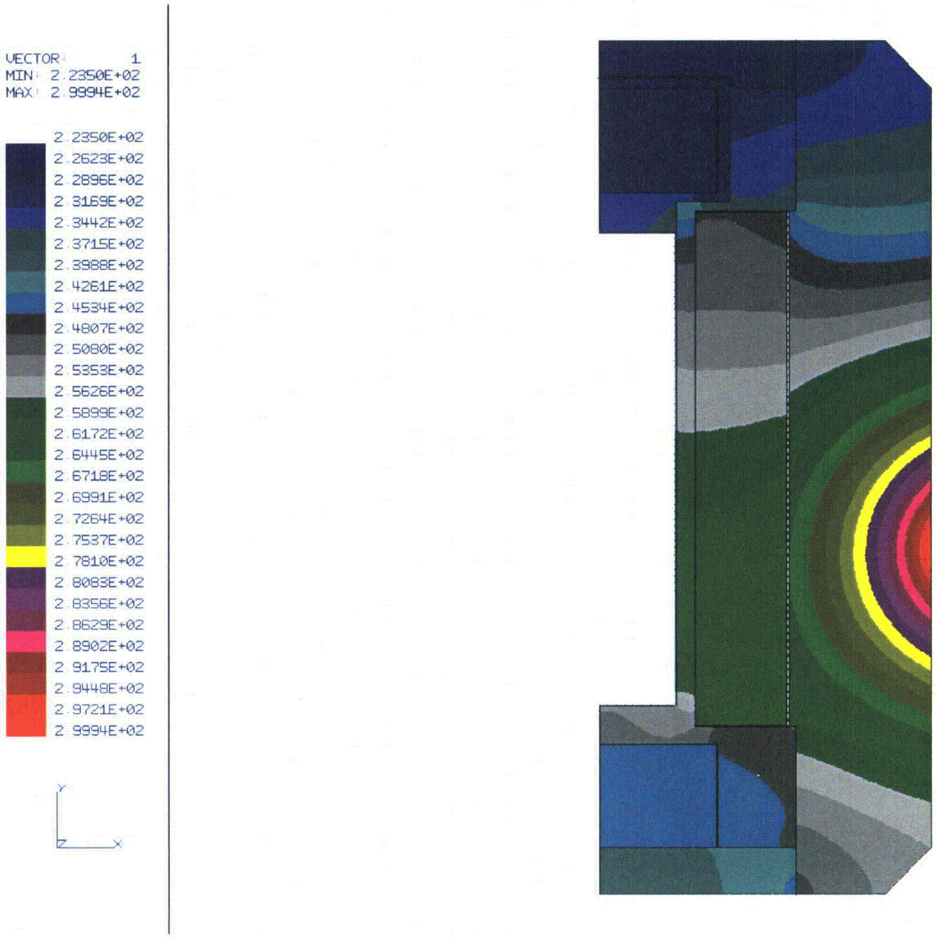

Figure 3-93. Load Case 111 – Fire at 30 Minutes, 1,475°F Ambient, Maximum Decay Heat, Cask Model – Model AOS-025

Table 3-75. Load Case 112 – Fire at 60 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation – Model AOS-025

Location	Node	Temp(C)	Temp(F)
1	5001	138.11	280.60
2	4532	141.72	287.10
3	4227	141.94	287.50
4	4752	138.94	282.10
5	4838	138.50	281.30
6	4995	137.78	280.00
7	3309	136.22	277.20
8	3419	137.28	279.10
9	678	141.61	286.90
10	2537	139.94	283.90
11	1888	143.06	289.50
12	583	143.28	289.90
13	3001	140.11	284.20
14	3148	141.56	286.80
15	7533	136.22	277.20
16	7377	136.33	277.40
17	7371	140.22	284.40
18	6942	141.39	286.50
19	6267	141.94	287.50
20	6121	140.94	285.70
21	6001	140.83	285.50
22	11481	136.44	277.60
23	12630	143.17	289.70
24	12694	146.78	296.20
25	13804	151.28	304.30
26	10926	158.11	316.60
27	9791	149.67	301.40
28	9577	144.94	292.90
29	8197	139.67	283.40
30	11451	135.61	276.10
31	11961	132.89	271.20
32	13022	144.44	292.00
33	13551	154.33	309.80
34	10673	159.78	319.60
35	9906	139.33	282.80
36	8673	113.33	236.00
37	8225	102.67	216.80

Maximum Component Temperatures

Component	Node_1	Node_2	Node	Max_Temp(C)	Max_Temp(F)
Outside Shell	101	2894	2807	1.4850E+02	2.9930E+02
Bottom Plate	3001	3232	3016	1.4756E+02	2.9760E+02
Lid	3233	3424	3309	1.4883E+02	2.9990E+02
Shell Cavity	4001	4998	4747	1.4850E+02	2.9930E+02
Plug	5001	5404	5001	1.4933E+02	3.0080E+02
Tungsten	6001	7656	7377	1.4856E+02	2.9940E+02
LAST-A-FOAM	8001	15086	10045	3.0106E+02	5.7390E+02

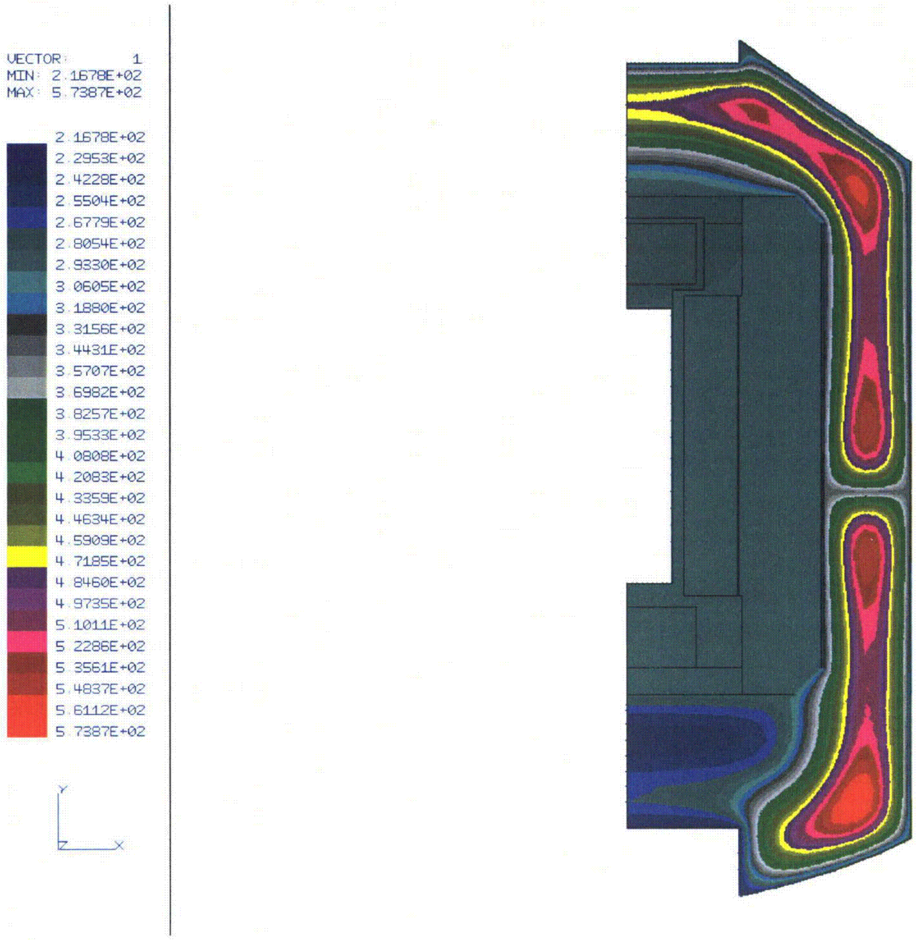

Figure 3-94. Load Case 112 – Fire at 60 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Entire Model – Model AOS-025

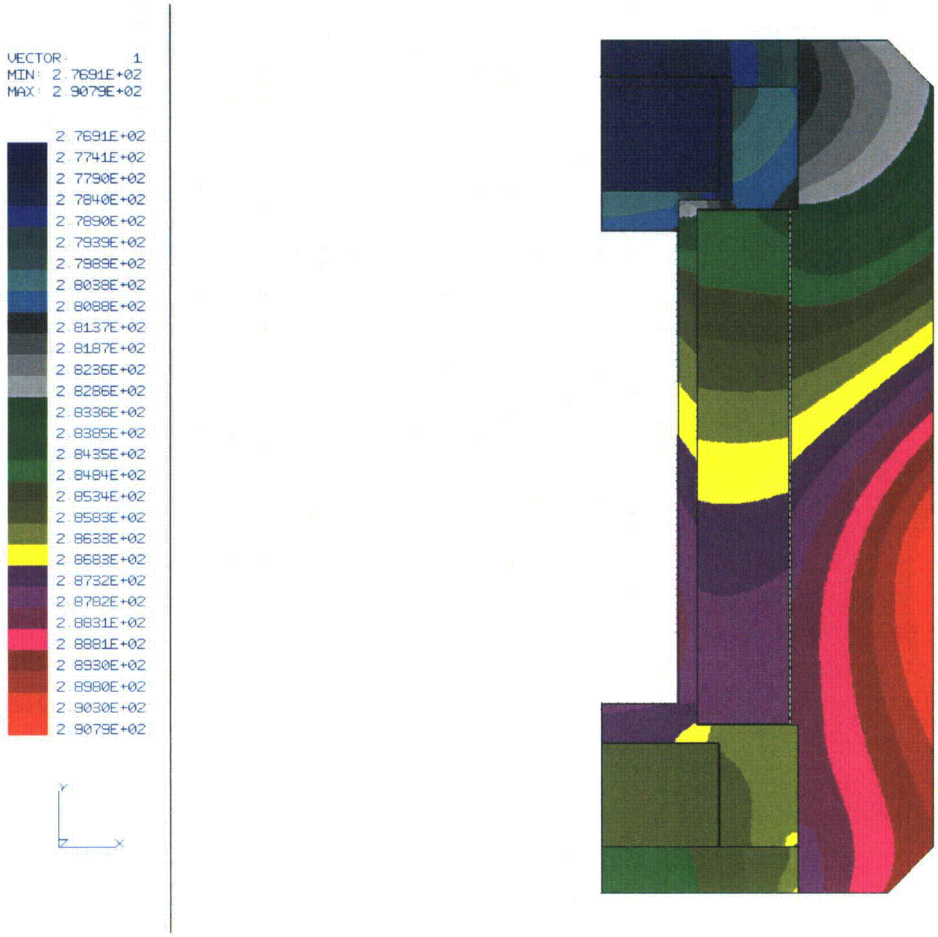

Figure 3-95. Load Case 112 – Fire at 60 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Cask Model – Model AOS-025

Table 3-76. Load Case 113 – Fire at 90 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation – Model AOS-025

Location	Node	Temp(C)	Temp(F)
1	5001	147.28	297.10
2	4532	146.89	296.40
3	4227	146.94	296.50
4	4752	146.72	296.10
5	4838	146.56	295.80
6	4995	146.67	296.00
7	3309	146.94	296.50
8	3419	147.00	296.60
9	678	146.39	295.50
10	2537	146.89	296.40
11	1888	146.28	295.30
12	583	146.56	295.80
13	3001	145.89	294.60
14	3148	146.33	295.40
15	7533	146.39	295.50
16	7377	146.44	295.60
17	7371	146.56	295.80
18	6942	146.44	295.60
19	6267	146.39	295.50
20	6121	146.17	295.10
21	6001	146.11	295.00
22	11481	147.39	297.30
23	12630	149.33	300.80
24	12694	150.28	302.50
25	13804	150.06	302.10
26	10926	147.94	298.30
27	9791	149.56	301.20
28	9577	148.11	298.60
29	8197	145.72	294.30
30	11451	110.06	230.10
31	11961	107.78	226.00
32	13022	111.56	232.80
33	13551	115.83	240.50
34	10673	120.72	249.30
35	9906	98.72	209.70
36	8673	78.67	173.60
37	8225	75.00	167.00

Maximum Component Temperatures

Component	Node_1	Node_2	Node	Max_Temp(C)	Max_Temp(F)
Outside Shell	101	2894	2807	1.4850E+02	2.9930E+02
Bottom Plate	3001	3232	3016	1.4756E+02	2.9760E+02
Lid	3233	3424	3309	1.4883E+02	2.9990E+02
Shell Cavity	4001	4998	4747	1.4850E+02	2.9930E+02
Plug	5001	5404	5001	1.4933E+02	3.0080E+02
Tungsten	6001	7656	7377	1.4856E+02	2.9940E+02
LAST-A-FOAM	8001	15086	10045	3.0106E+02	5.7390E+02

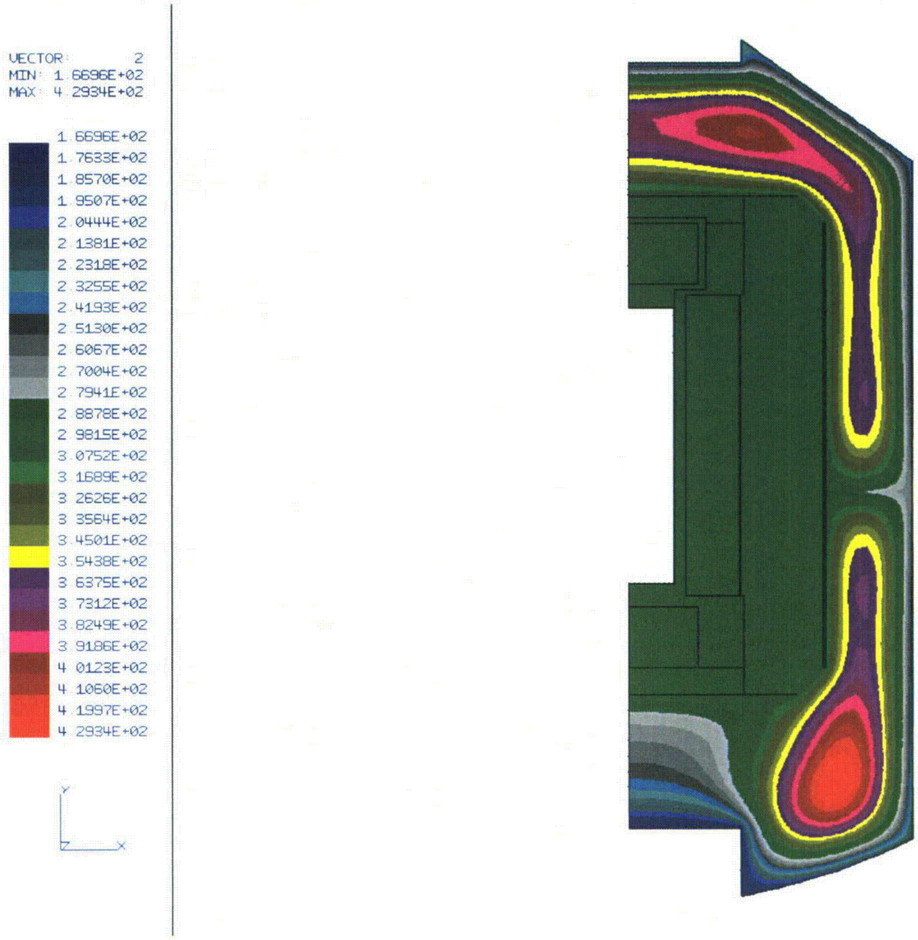

Figure 3-96. Load Case 113 – Fire at 90 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Entire Model – Model AOS-025

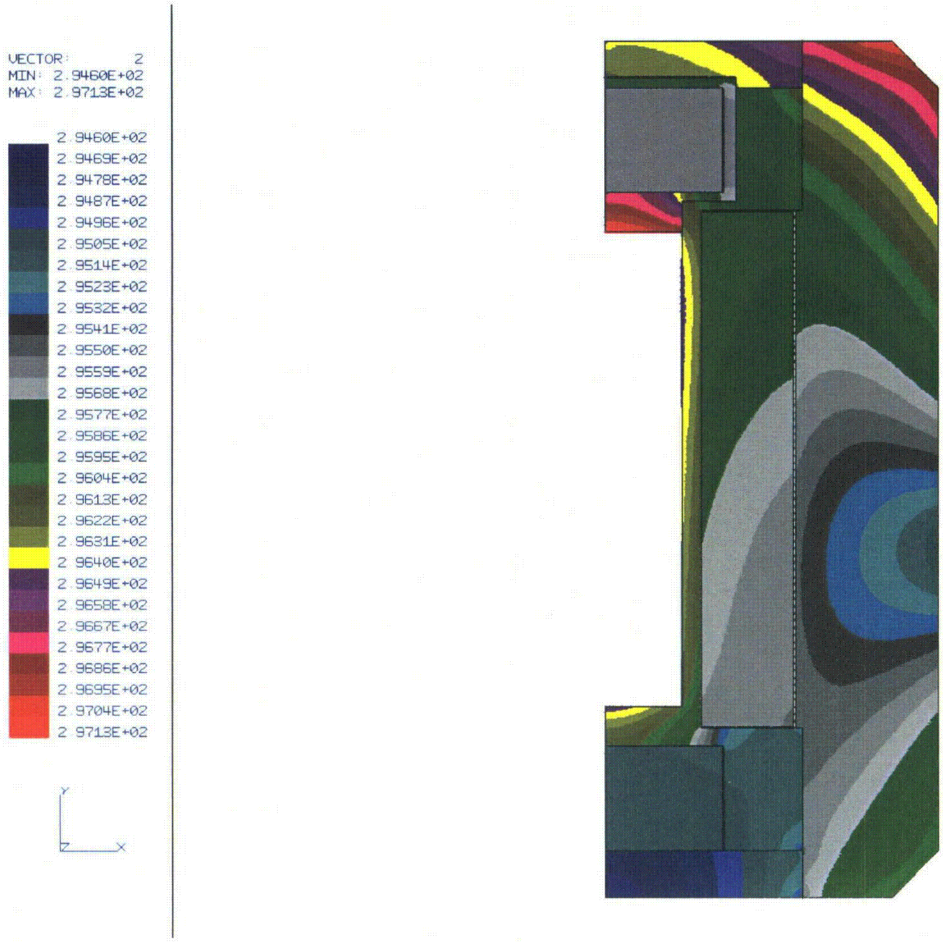

Figure 3-97. Load Case 113 – Fire at 90 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Cask Model – Model AOS-025

Table 3-77. Load Case 114 – Fire at 120 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation – Model AOS-025

Location	Node	Temp(C)	Temp(F)
1	5001	149.33	300.80
2	4532	148.17	298.70
3	4227	148.39	299.10
4	4752	148.50	299.30
5	4838	148.17	298.70
6	4995	148.33	299.00
7	3309	148.83	299.90
8	3419	148.67	299.60
9	678	147.61	297.70
10	2537	148.11	298.60
11	1888	147.00	296.60
12	583	147.28	297.10
13	3001	147.50	297.50
14	3148	147.56	297.60
15	7533	148.56	299.40
16	7377	148.56	299.40
17	7371	148.00	298.40
18	6942	147.72	297.90
19	6267	147.61	297.70
20	6121	147.61	297.70
21	6001	147.61	297.70
22	11481	149.11	300.40
23	12630	149.06	300.30
24	12694	149.00	300.20
25	13804	147.89	298.20
26	10926	144.06	291.30
27	9791	148.17	298.70
28	9577	148.17	298.70
29	8197	147.39	297.30
30	11451	101.67	215.00
31	11961	99.44	211.00
32	13022	99.78	211.60
33	13551	101.89	215.40
34	10673	107.50	225.50
35	9906	83.89	183.00
36	8673	66.56	151.80
37	8225	65.44	149.80

Maximum Component Temperatures

Component	Node_1	Node_2	Node	Max_Temp(C)	Max_Temp(F)
Outside Shell	101	2894	2807	1.4850E+02	2.9930E+02
Bottom Plate	3001	3232	3016	1.4756E+02	2.9760E+02
Lid	3233	3424	3309	1.4883E+02	2.9990E+02
Shell Cavity	4001	4998	4747	1.4850E+02	2.9930E+02
Plug	5001	5404	5001	1.4933E+02	3.0080E+02
Tungsten	6001	7656	7377	1.4856E+02	2.9940E+02
LAST-A-FOAM	8001	15086	10045	3.0106E+02	5.7390E+02

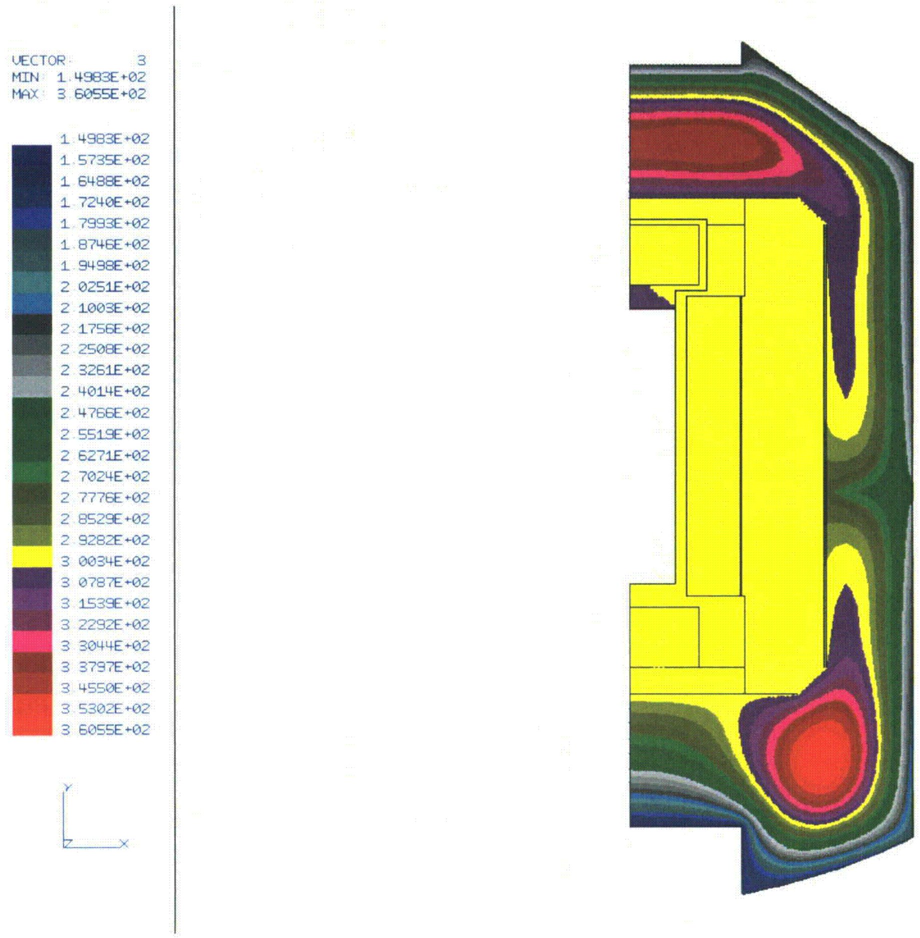

Figure 3-98. Load Case 114 – Fire at 120 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Entire Model – Model AOS-025

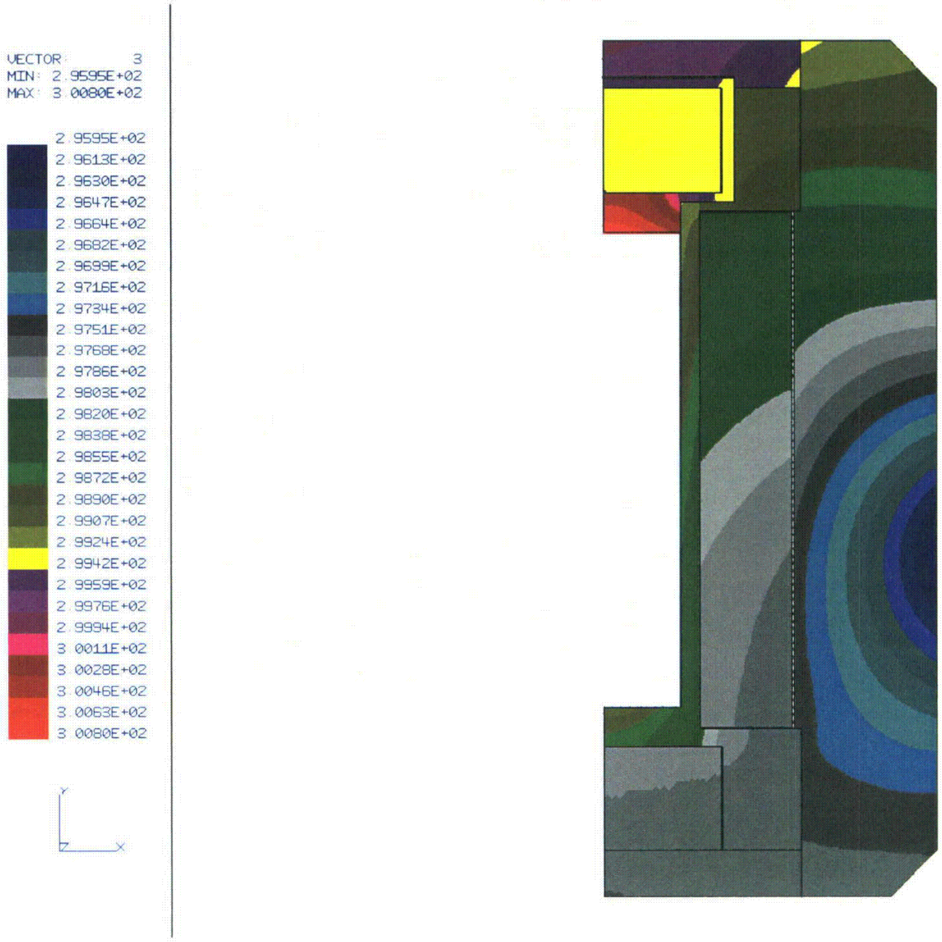

Figure 3-99. Load Case 114 – Fire at 120 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Cask Model – Model AOS-025

Table 3-78. Load Case 115 – Fire at 150 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation – Model AOS-025

Location	Node	Temp(C)	Temp(F)
1	5001	148.89	300.00
2	4532	147.67	297.80
3	4227	148.00	298.40
4	4752	148.00	298.40
5	4838	147.61	297.70
6	4995	147.72	297.90
7	3309	148.11	298.60
8	3419	147.89	298.20
9	678	147.06	296.70
10	2537	147.39	297.30
11	1888	146.33	295.40
12	583	146.61	295.90
13	3001	147.11	296.80
14	3148	147.06	296.70
15	7533	148.06	298.50
16	7377	148.11	298.60
17	7371	147.44	297.40
18	6942	147.22	297.00
19	6267	147.11	296.80
20	6121	147.28	297.10
21	6001	147.22	297.00
22	11481	148.22	298.80
23	12630	147.50	297.50
24	12694	147.11	296.80
25	13804	145.89	294.60
26	10926	141.72	287.10
27	9791	146.39	295.50
28	9577	146.94	296.50
29	8197	147.06	296.70
30	11451	97.50	207.50
31	11961	95.50	203.90
32	13022	94.56	202.20
33	13551	96.00	204.80
34	10673	102.00	215.60
35	9906	76.67	170.00
36	8673	60.56	141.00
37	8225	60.67	141.20

Maximum Component Temperatures

Component	Node_1	Node_2	Node	Max_Temp(C)	Max_Temp(F)
Outside Shell	101	2894	2807	1.4850E+02	2.9930E+02
Bottom Plate	3001	3232	3016	1.4756E+02	2.9760E+02
Lid	3233	3424	3309	1.4883E+02	2.9990E+02
Shell Cavity	4001	4998	4747	1.4850E+02	2.9930E+02
Plug	5001	5404	5001	1.4933E+02	3.0080E+02
Tungsten	6001	7656	7377	1.4856E+02	2.9940E+02
LAST-A-FOAM	8001	15086	10045	3.0106E+02	5.7390E+02

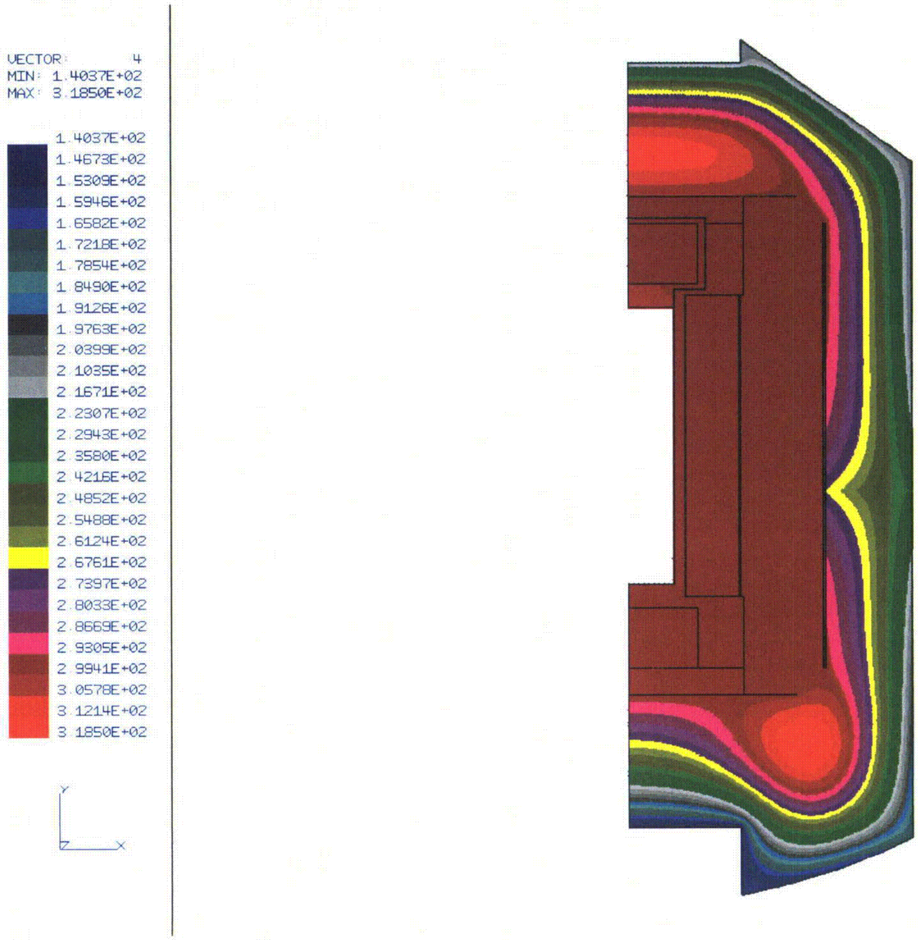

Figure 3-100. Load Case 115 – Fire at 150 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Entire Model – Model AOS-025

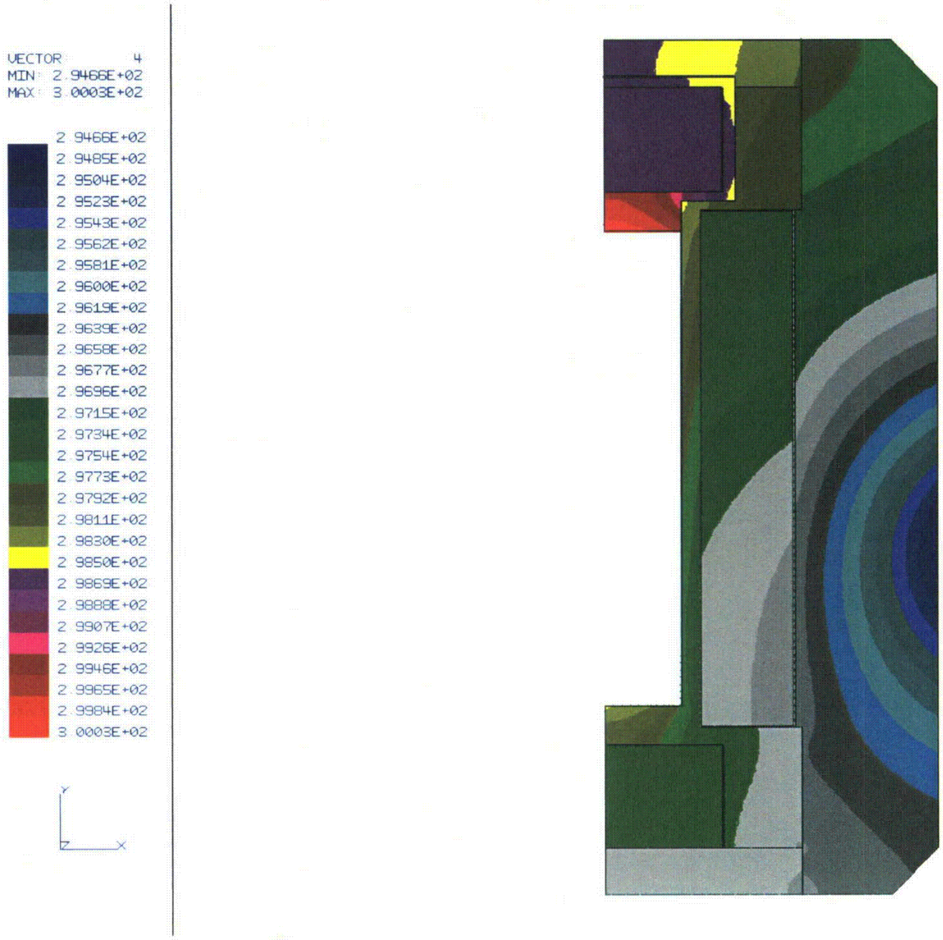

Figure 3-101. Load Case 115 – Fire at 150 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Cask Model – Model AOS-025

Table 3-79. Load Case 116 – Fire at 180 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation – Model AOS-025

Location	Node	Temp(C)	Temp(F)
1	5001	147.61	297.70
2	4532	146.39	295.50
3	4227	146.72	296.10
4	4752	146.67	296.00
5	4838	146.28	295.30
6	4995	146.33	295.40
7	3309	146.56	295.80
8	3419	146.39	295.50
9	678	145.78	294.40
10	2537	145.94	294.70
11	1888	145.00	293.00
12	583	145.28	293.50
13	3001	145.83	294.50
14	3148	145.67	294.20
15	7533	146.72	296.10
16	7377	146.78	296.20
17	7371	146.17	295.10
18	6942	145.94	294.70
19	6267	145.83	294.50
20	6121	146.00	294.80
21	6001	146.00	294.80
22	11481	146.61	295.90
23	12630	145.67	294.20
24	12694	145.11	293.20
25	13804	144.00	291.20
26	10926	139.83	283.70
27	9791	144.44	292.00
28	9577	145.17	293.30
29	8197	145.72	294.30
30	11451	95.17	203.30
31	11961	93.33	200.00
32	13022	92.11	197.80
33	13551	93.33	200.00
34	10673	99.33	210.80
35	9906	72.61	162.70
36	8673	57.06	134.70
37	8225	57.61	135.70

Maximum Component Temperatures

Component	Node_1	Node_2	Node	Max_Temp(C)	Max_Temp(F)
Outside Shell	101	2894	2807	1.4850E+02	2.9930E+02
Bottom Plate	3001	3232	3016	1.4756E+02	2.9760E+02
Lid	3233	3424	3309	1.4883E+02	2.9990E+02
Shell Cavity	4001	4998	4747	1.4850E+02	2.9930E+02
Plug	5001	5404	5001	1.4933E+02	3.0080E+02
Tungsten	6001	7656	7377	1.4856E+02	2.9940E+02
LAST-A-FOAM	8001	15086	10045	3.0106E+02	5.7390E+02

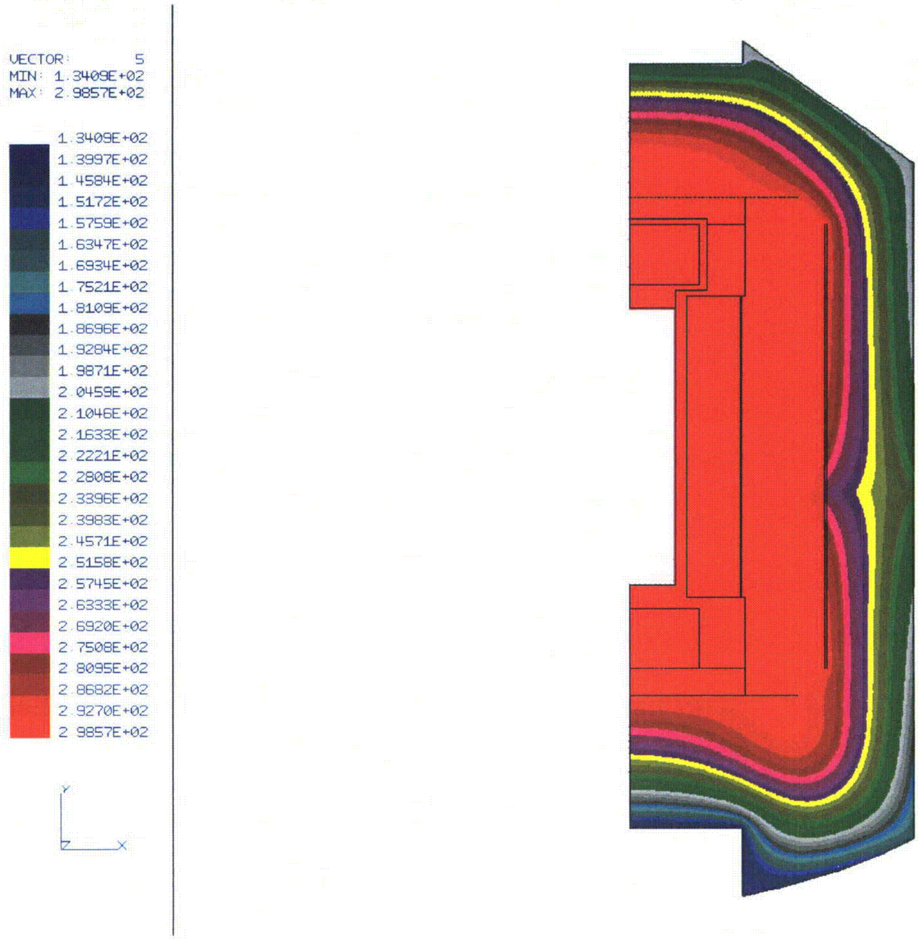

Figure 3-102. Load Case 116 – Fire at 180 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Entire Model – Model AOS-025

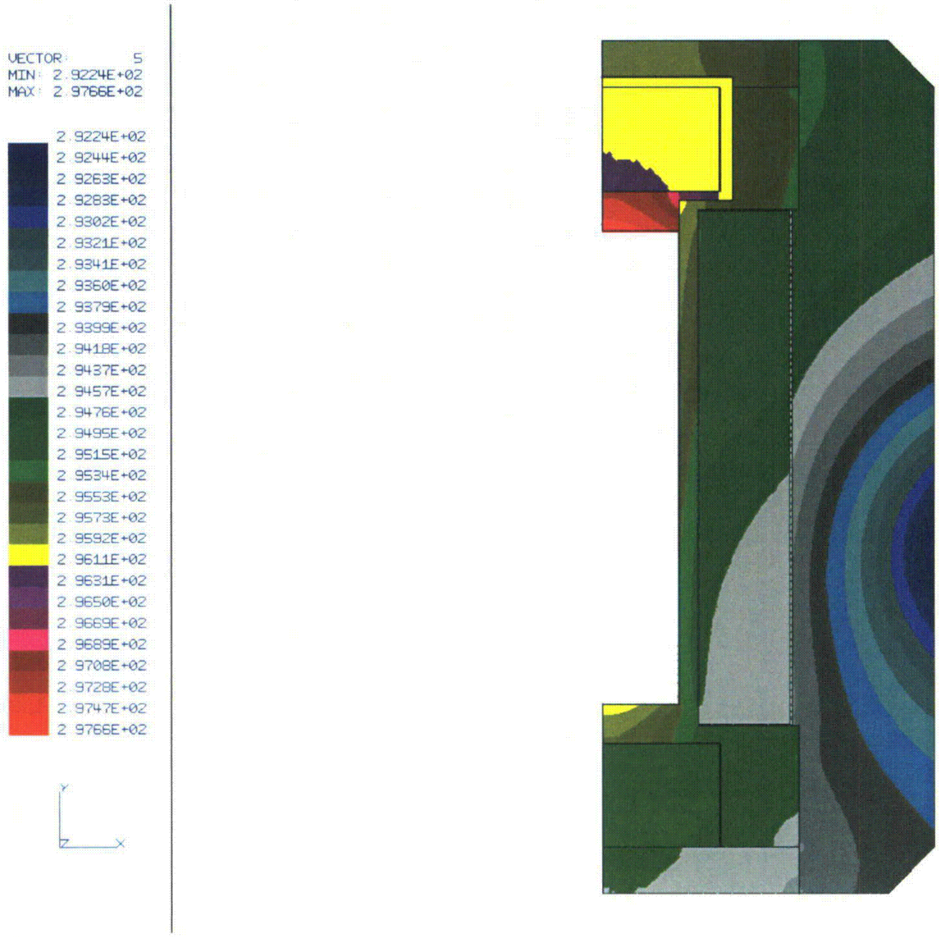

Figure 3-103. Load Case 116 – Fire at 180 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Cask Model – Model AOS-025

3.5.2.2 Hypothetical Accident Conditions of Transport Results – Model AOS-050

Table 3-80 lists the tables and figures in this appendix that present the Model AOS-050 transport package results under Hypothetical Accident conditions of transport, for Load Cases 111 through 116. Each table provides a list of temperatures at each monitoring node. Also listed are the maximum temperatures within each transport package component.

Table 3-81 lists the temperature monitoring points (nodes) for the Model AOS-050 transport package, under Normal and Hypothetical Accident (Fire) conditions of transport. Figure 3-104 illustrates the location of each node on the transport package, under Fire conditions.

Table 3-80. Hypothetical Accident Conditions of Transport Results – Model AOS-050

Load Case	Description	Results Table	Temperature versus Time	Entire Model	Cask Model
111	Fire at 30 Minutes, 1,475°F Ambient, Maximum Decay Heat	Table 3-82	Figure 3-105	Figure 3-106	Figure 3-107
112	Fire at 60 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation	Table 3-83	–	Figure 3-108	Figure 3-109
113	Fire at 90 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation	Table 3-84	–	Figure 3-110	Figure 3-111
114	Fire at 120 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation	Table 3-85	–	Figure 3-112	Figure 3-113
115	Fire at 150 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation	Table 3-86	–	Figure 3-114	Figure 3-115
116	Fire at 180 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation	Table 3-87	–	Figure 3-116	Figure 3-117

Table 3-81. Temperature Monitoring Points, All Conditions of Transport – Model AOS-050

Nodal Location	LIBRA Model Nodal Number	
	Normal Conditions	Fire Conditions
1	5001	5001
2	4532	4532
3	4227	4227
4	4752	4752
5	4838	4838
6	4995	4995
7	3309	3309
8	3419	3419
9	678	678
10	2537	2537
11	1888	1888
12	583	583
13	3001	3001
14	3148	3148
15	7533	7533
16	7377	7377
17	7371	7371
18	6942	6942
19	6267	6267
20	6121	6121
21	6001	6001
22	9501	15481
23	9950	16630
24	10014	16694
25	10781	17804
26	9091	11128
27	8463	9785
28	8462	9571
29	8197	8197
30	9711	15451
31	9821	15961
32	10158	17022
33	10605	17551
34	9102	10798
35	8578	9900
36	8225	8673
37	8001	8225

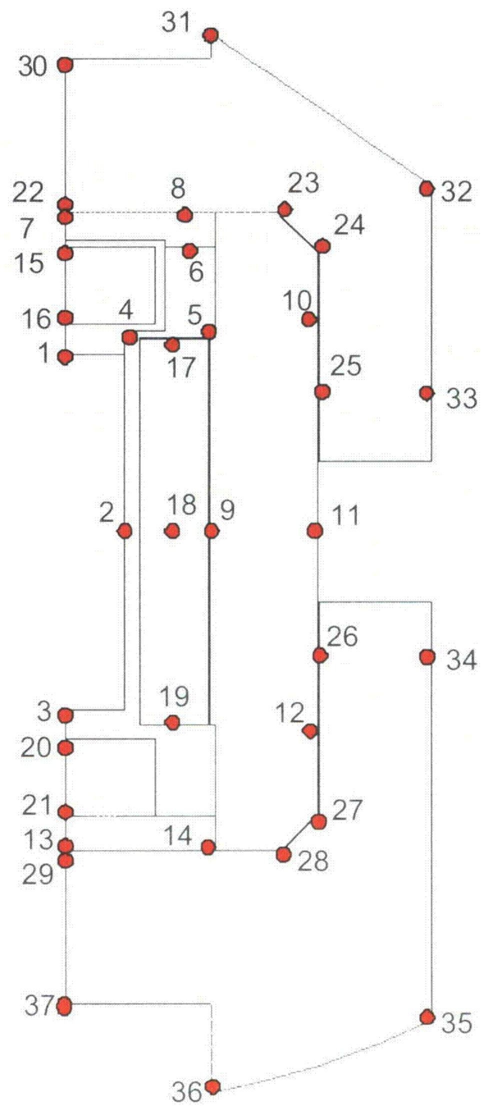

Figure 3-104. Selected Nodal Locations for Fire Conditions of Transport – Model AOS-050

Table 3-82. Load Case 111 – Fire at 30 Minutes, 1,475°F Ambient, Maximum Decay Heat – Model AOS-050

Location	Node	Temp(C)	Temp(F)
1	5001	154.61	310.30
2	4532	214.44	418.00
3	4227	165.83	330.50
4	4752	172.33	342.20
5	4838	165.06	329.10
6	4995	145.28	293.50
7	3309	131.56	268.80
8	3419	136.61	277.90
9	678	238.44	461.20
10	2537	176.28	349.30
11	1888	374.22	705.60
12	583	175.17	347.30
13	3001	134.56	274.20
14	3148	140.83	285.50
15	7533	139.67	283.40
16	7377	141.33	286.40
17	7371	195.39	383.70
18	6942	218.28	424.90
19	6267	194.11	381.40
20	6121	148.06	298.50
21	6001	145.39	293.70
22	15481	131.06	267.90
23	16630	142.44	288.40
24	16694	146.89	296.40
25	17804	289.44	553.00
26	11128	289.39	552.90
27	9785	148.06	298.50
28	9571	143.11	289.60
29	8197	133.44	272.20
30	15451	795.56	1464.00
31	15961	799.44	1471.00
32	17022	797.78	1468.00
33	17551	796.11	1465.00
34	10798	797.22	1467.00
35	9900	798.33	1469.00
36	8673	608.89	1128.00
37	8225	111.89	233.40

Maximum Component Temperatures

Component	Node_1	Node_2	Node	Max_Temp(C)	Max_Temp(F)
Outside Shell	101	2894	1888	3.7422E+02	7.0560E+02
Bottom Plate	3001	3232	3148	1.4083E+02	2.8550E+02
Lid	3233	3424	3360	1.4022E+02	2.8440E+02
Shell Cavity	4001	4998	4536	2.1467E+02	4.1840E+02
Plug	5001	5404	5012	1.6022E+02	3.2040E+02
Tungsten Alloy	6001	7656	6949	2.2367E+02	4.3460E+02
LAST-A-FOAM	8001	18462	15929	7.9944E+02	1.4710E+03

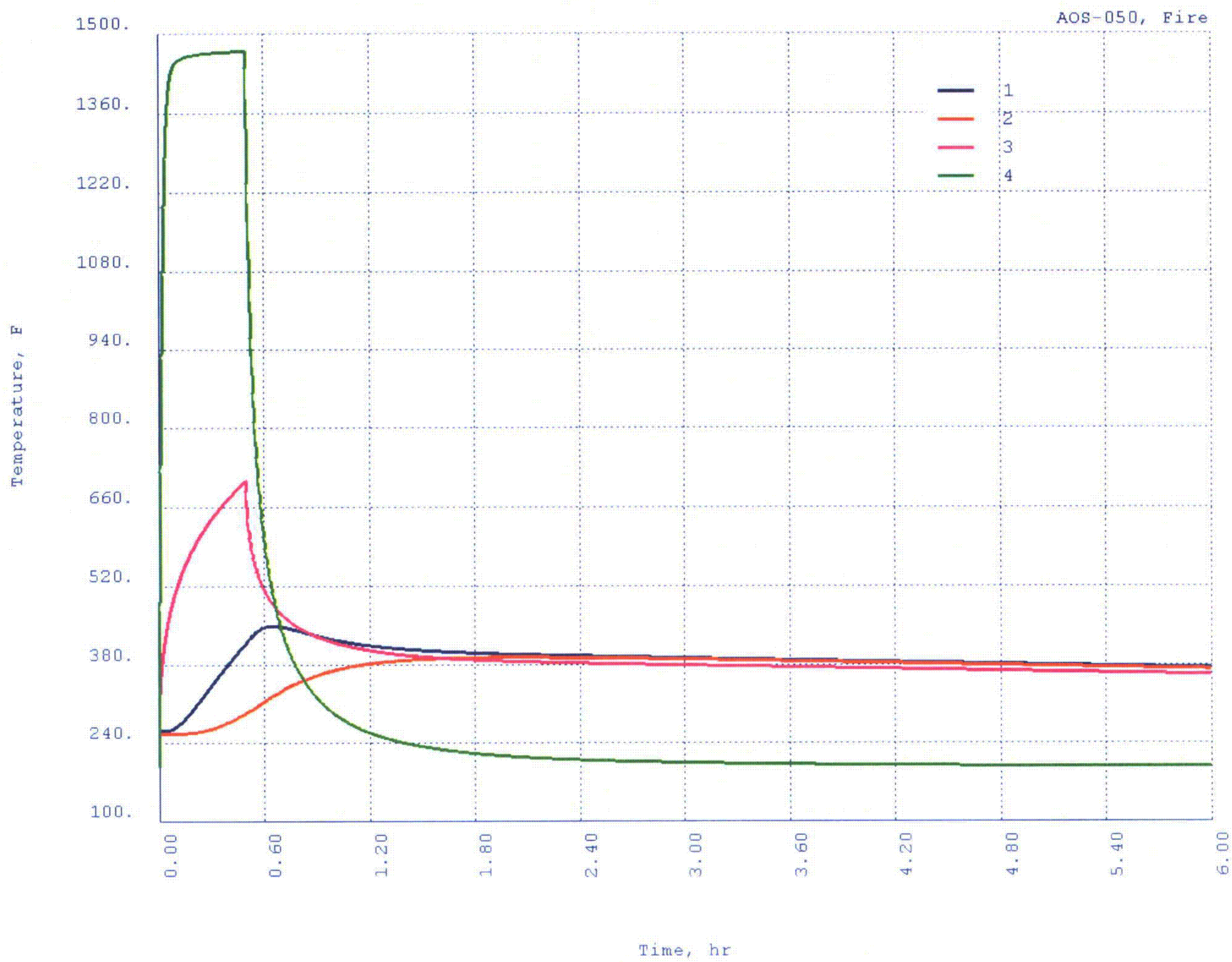

Figure 3-105. Load Case 111 – Fire at 30 Minutes, 1,475°F Ambient, Maximum Decay Heat, Temperature versus Time – Model AOS-050

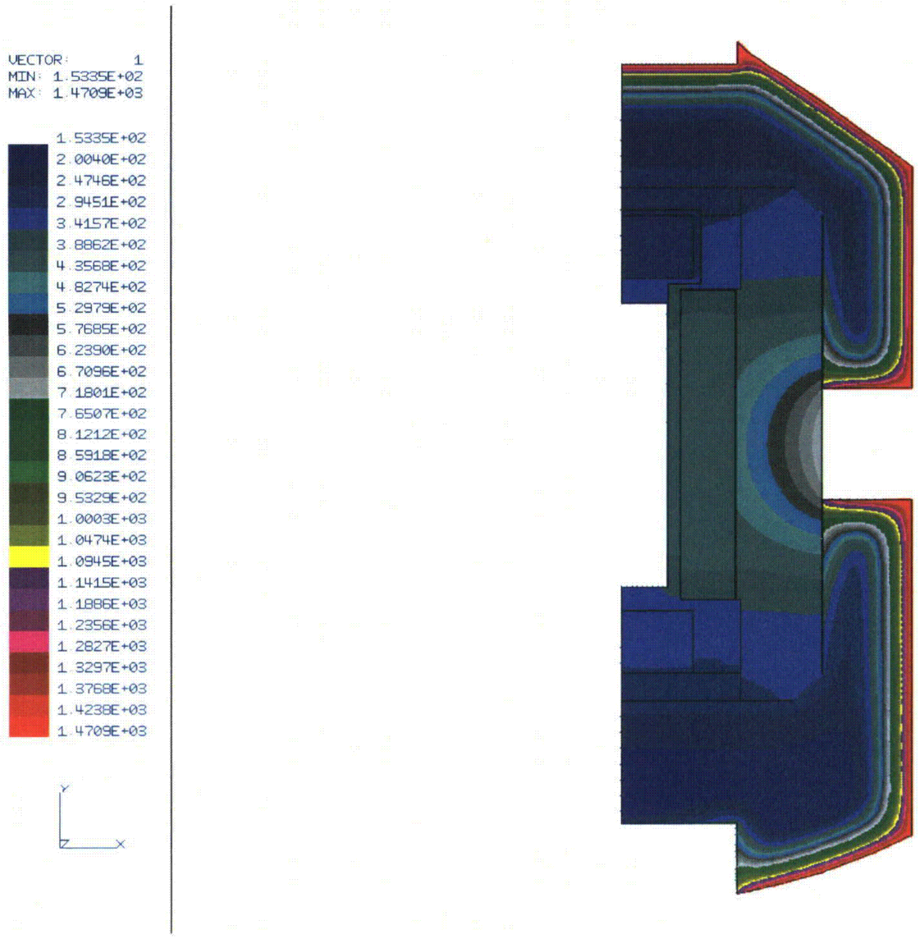

Figure 3-106. Load Case 111 – Fire at 30 Minutes, 1,475°F Ambient, Maximum Decay Heat, Entire Model – Model AOS-050

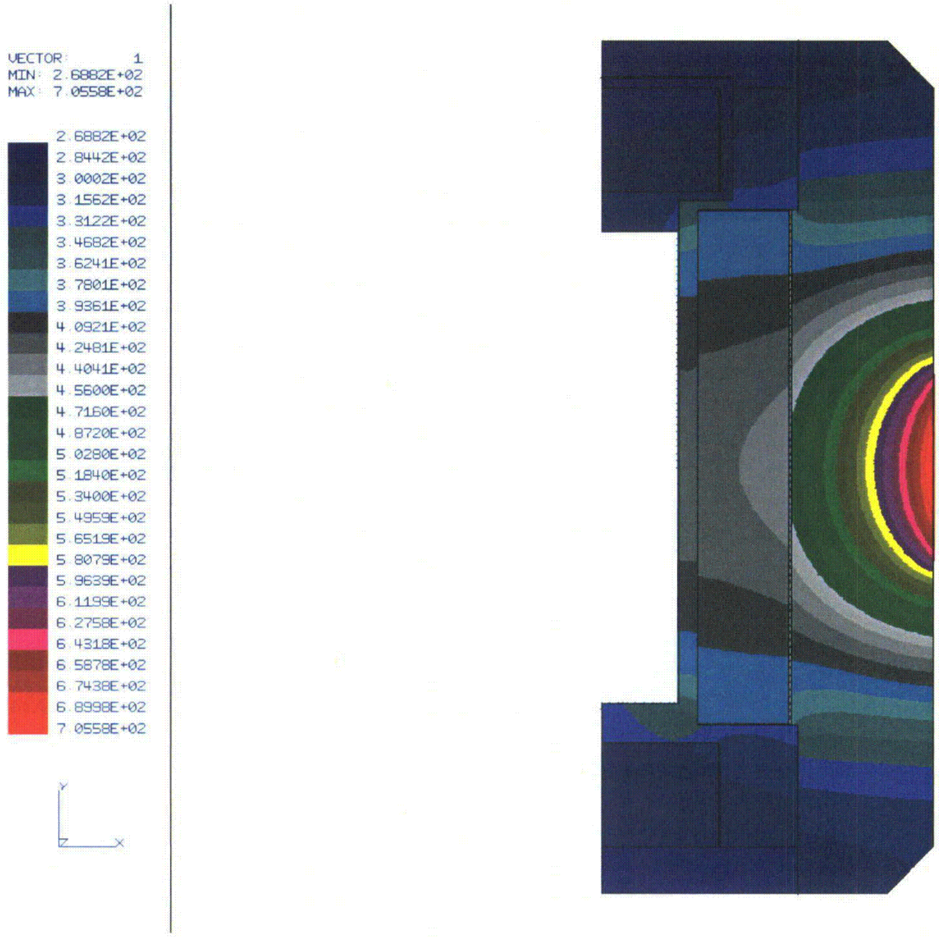

Figure 3-107. Load Case 111 – Fire at 30 Minutes, 1,475°F Ambient, Maximum Decay Heat, Cask Model – Model AOS-050

Table 3-83. Load Case 112 – Fire at 60 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation – Model AOS-050

Location	Node	Temp(C)	Temp(F)
1	5001	193.44	380.20
2	4532	217.17	422.90
3	4227	201.89	395.40
4	4752	200.56	393.00
5	4838	197.17	386.90
6	4995	187.44	369.40
7	3309	173.33	344.00
8	3419	179.89	355.80
9	678	215.72	420.30
10	2537	199.50	391.10
11	1888	214.44	418.00
12	583	199.39	390.90
13	3001	178.56	353.40
14	3148	184.72	364.50
15	7533	181.39	358.50
16	7377	182.72	360.90
17	7371	209.44	409.00
18	6942	215.00	419.00
19	6267	209.06	408.30
20	6121	190.06	374.10
21	6001	188.17	370.70
22	15481	172.39	342.30
23	16630	185.39	365.70
24	16694	186.44	367.60
25	17804	202.33	396.20
26	11128	201.83	395.30
27	9785	186.83	368.30
28	9571	185.78	366.40
29	8197	177.11	350.80
30	15451	141.00	285.80
31	15961	134.83	274.70
32	17022	143.67	290.60
33	17551	148.50	299.30
34	10798	142.50	288.50
35	9900	132.33	270.20
36	8673	102.67	216.80
37	8225	78.78	173.80

Maximum Component Temperatures

Component	Node_1	Node_2	Node	Max_Temp(C)	Max_Temp(F)
Outside Shell	101	2894	1117	2.1633E+02	4.2140E+02
Bottom Plate	3001	3232	3120	2.0006E+02	3.9210E+02
Lid	3233	3424	3233	1.9978E+02	3.9160E+02
Shell Cavity	4001	4998	4522	2.1717E+02	4.2290E+02
Plug	5001	5404	5001	2.0489E+02	4.0080E+02
Tungsten	6001	7656	6440	2.1522E+02	4.1940E+02
LAST-A-FOAM	8001	18462	18017	3.3217E+02	6.2990E+02

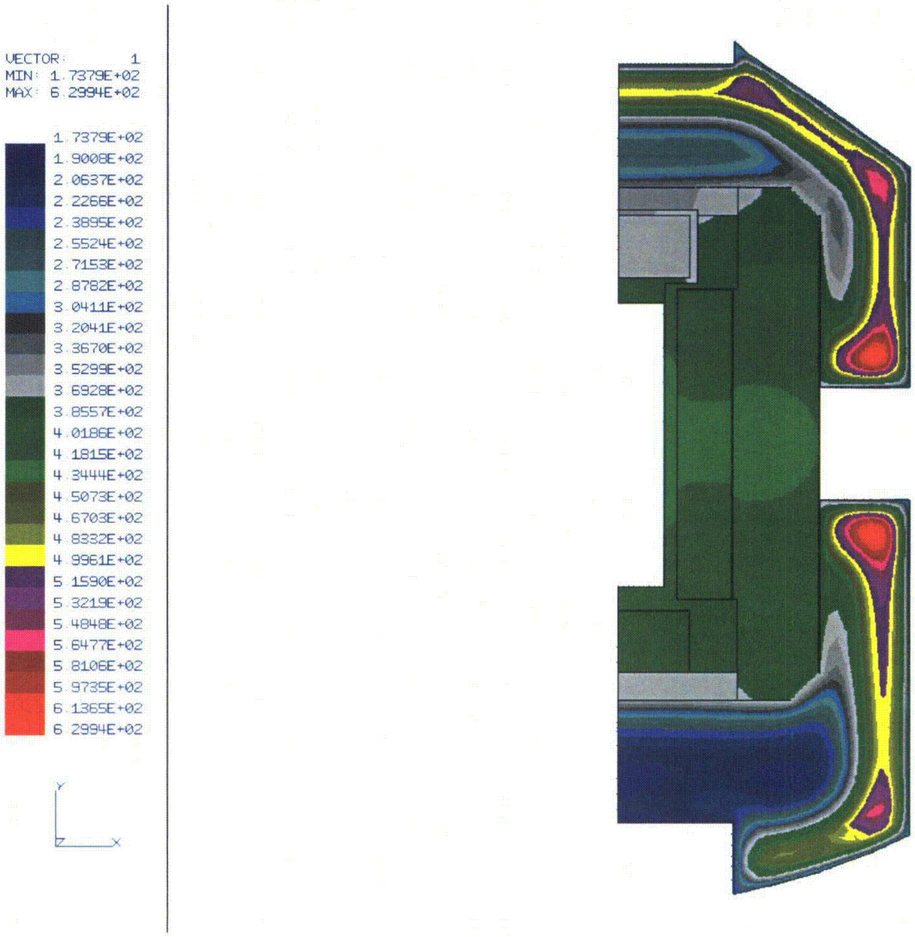

Figure 3-108. Load Case 112 – Fire at 60 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Entire Model – Model AOS-050

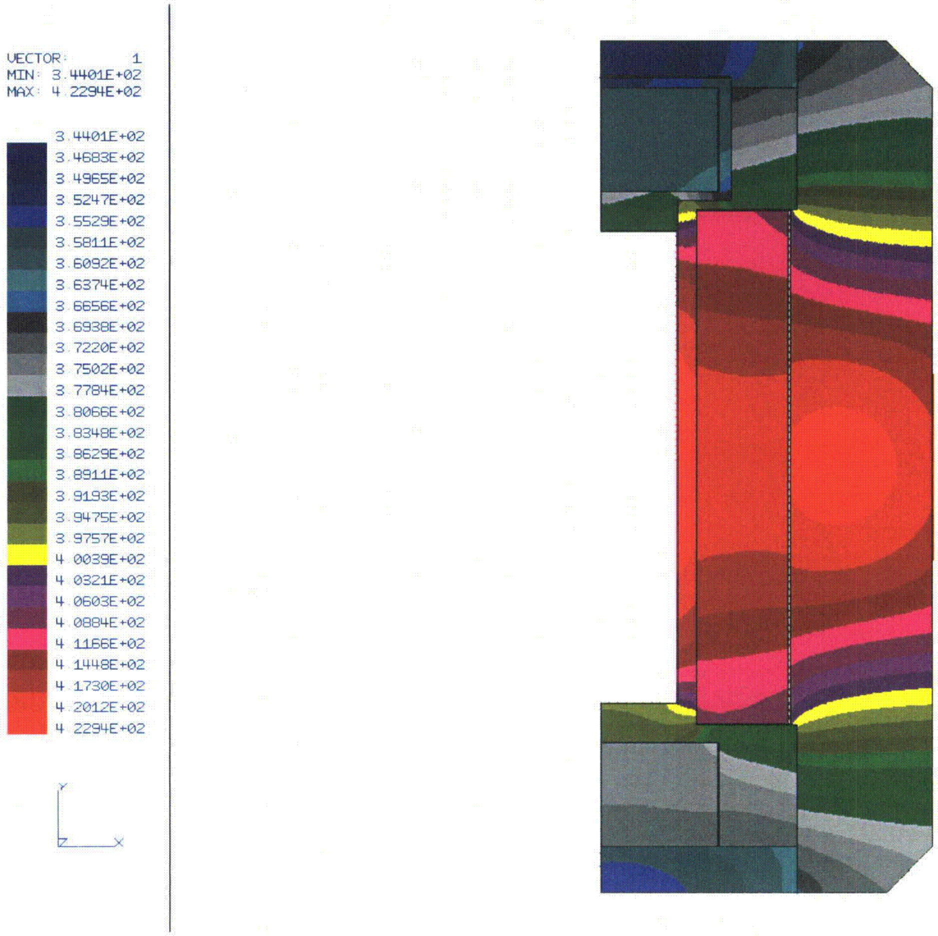

Figure 3-109. Load Case 112 – Fire at 60 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Cask Model – Model AOS-050

Table 3-84. Load Case 113 – Fire at 90 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation – Model AOS-050

Location	Node	Temp(C)	Temp(F)
1	5001	203.17	397.70
2	4532	206.72	404.10
3	4227	205.00	401.00
4	4752	202.50	396.50
5	4838	200.44	392.80
6	4995	198.11	388.60
7	3309	194.22	381.60
8	3419	196.06	384.90
9	678	204.06	399.30
10	2537	200.28	392.50
11	1888	200.56	393.00
12	583	200.67	393.20
13	3001	196.44	385.60
14	3148	197.78	388.00
15	7533	197.17	386.90
16	7377	197.67	387.80
17	7371	203.39	398.10
18	6942	204.61	400.30
19	6267	203.61	398.50
20	6121	199.89	391.80
21	6001	199.33	390.80
22	15481	193.67	380.60
23	16630	197.61	387.70
24	16694	198.00	388.40
25	17804	192.61	378.70
26	11128	193.83	380.90
27	9785	197.61	387.70
28	9571	197.22	387.00
29	8197	195.67	384.20
30	15451	113.44	236.20
31	15961	108.89	228.00
32	17022	111.11	232.00
33	17551	110.39	230.70
34	10798	109.28	228.70
35	9900	90.61	195.10
36	8673	66.39	151.50
37	8225	58.17	136.70

Maximum Component Temperatures

Component	Node_1	Node_2	Node	Max_Temp(C)	Max_Temp(F)
Outside Shell	101	2894	1117	2.1633E+02	4.2140E+02
Bottom Plate	3001	3232	3120	2.0006E+02	3.9210E+02
Lid	3233	3424	3233	1.9978E+02	3.9160E+02
Shell Cavity	4001	4998	4522	2.1717E+02	4.2290E+02
Plug	5001	5404	5001	2.0489E+02	4.0080E+02
Tungsten	6001	7656	6440	2.1522E+02	4.1940E+02
LAST-A-FOAM	8001	18462	18017	3.3217E+02	6.2990E+02

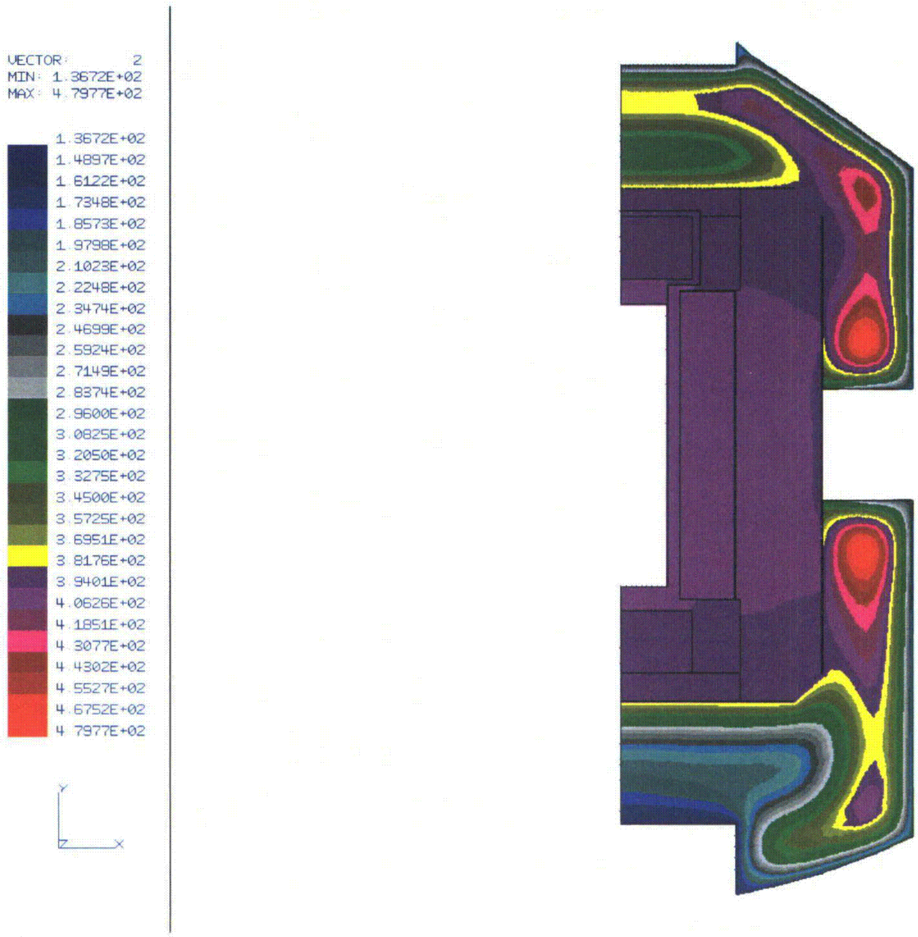

Figure 3-110. Load Case 113 – Fire at 90 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Entire Model – Model AOS-050

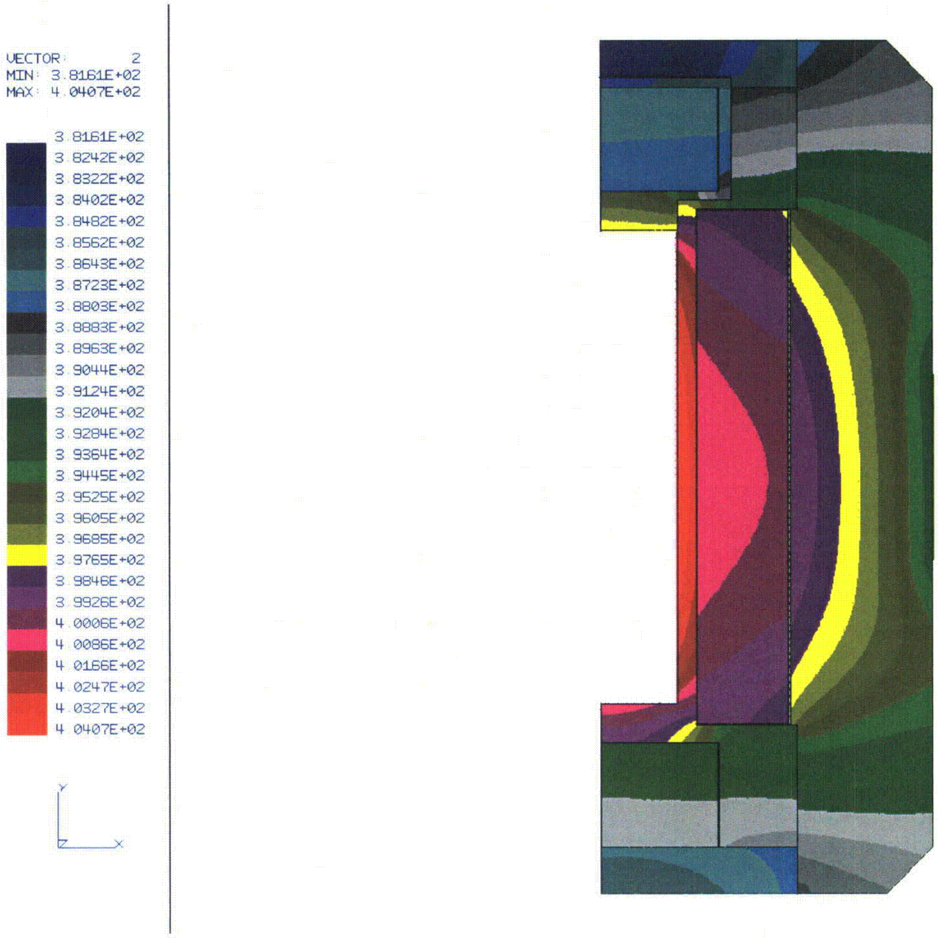

Figure 3-111. Load Case 113 – Fire at 90 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Cask Model – Model AOS-050

Table 3-85. Load Case 114 – Fire at 120 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation – Model AOS-050

Location	Node	Temp(C)	Temp(F)
1	5001	204.89	400.80
2	4532	202.94	397.30
3	4227	204.44	400.00
4	4752	202.11	395.80
5	4838	200.22	392.40
6	4995	199.89	391.80
7	3309	199.22	390.60
8	3419	199.44	391.00
9	678	200.06	392.10
10	2537	199.33	390.80
11	1888	196.11	385.00
12	583	199.67	391.40
13	3001	199.72	391.50
14	3148	199.72	391.50
15	7533	200.61	393.10
16	7377	200.89	393.60
17	7371	200.83	393.50
18	6942	200.89	393.60
19	6267	201.06	393.90
20	6121	201.00	393.80
21	6001	200.72	393.30
22	15481	198.89	390.00
23	16630	199.61	391.30
24	16694	199.67	391.40
25	17804	188.39	371.10
26	11128	189.94	373.90
27	9785	198.94	390.10
28	9571	198.94	390.10
29	8197	199.22	390.60
30	15451	105.72	222.30
31	15961	101.89	215.40
32	17022	101.44	214.60
33	17551	98.50	209.30
34	10798	99.56	211.20
35	9900	77.28	171.10
36	8673	54.83	130.70
37	8225	51.17	124.10

Maximum Component Temperatures

Component	Node_1	Node_2	Node	Max_Temp(C)	Max_Temp(F)
Outside Shell	101	2894	1117	2.1633E+02	4.2140E+02
Bottom Plate	3001	3232	3120	2.0006E+02	3.9210E+02
Lid	3233	3424	3233	1.9978E+02	3.9160E+02
Shell Cavity	4001	4998	4522	2.1717E+02	4.2290E+02
Plug	5001	5404	5001	2.0489E+02	4.0080E+02
Tungsten	6001	7656	6440	2.1522E+02	4.1940E+02
LAST-A-FOAM	8001	18462	18017	3.3217E+02	6.2990E+02

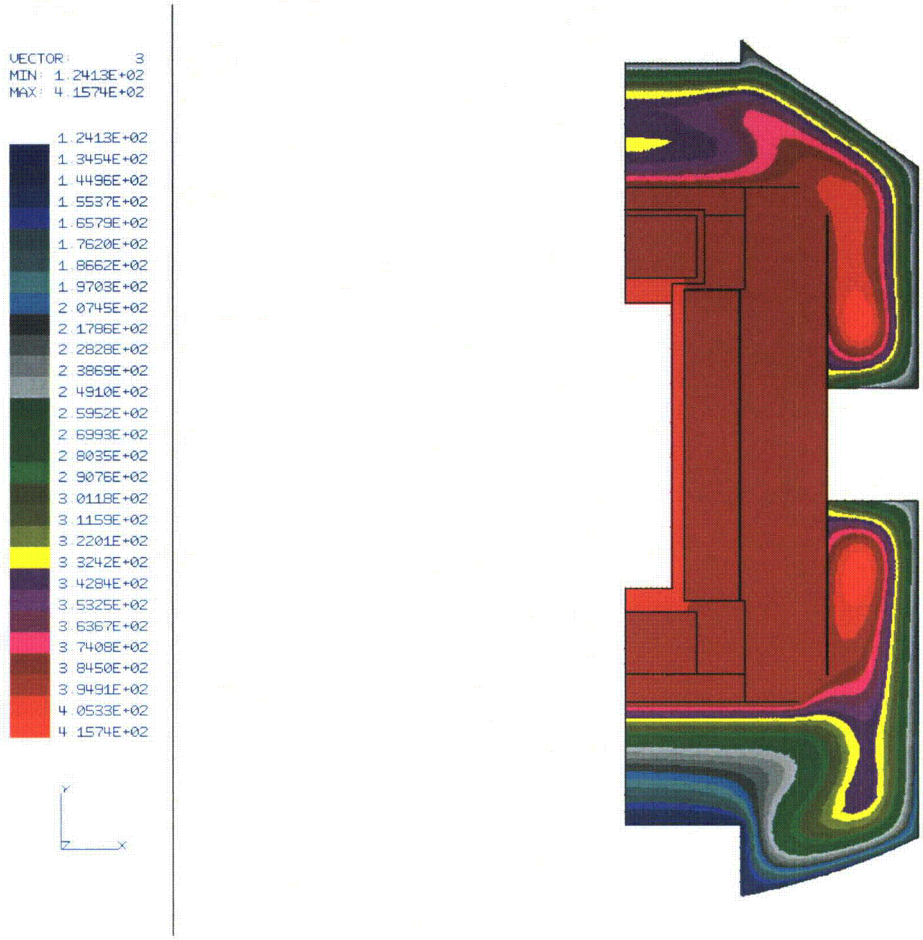

Figure 3-112. Load Case 114 – Fire at 120 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Entire Model – Model AOS-050

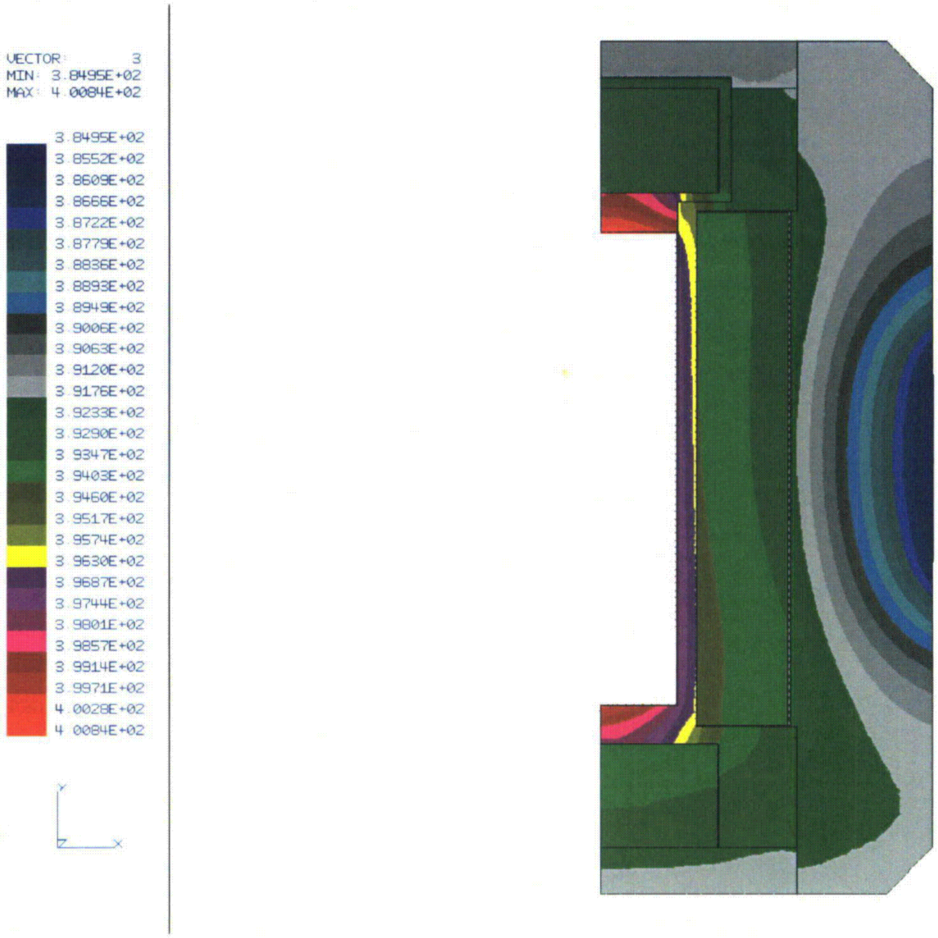

Figure 3-113. Load Case 114 – Fire at 120 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Cask Model – Model AOS-050

Table 3-86. Load Case 115 – Fire at 150 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation – Model AOS-050

Location	Node	Temp(C)	Temp(F)
1	5001	204.39	399.90
2	4532	200.89	393.60
3	4227	203.11	397.60
4	4752	201.00	393.80
5	4838	199.11	390.40
6	4995	199.33	390.80
7	3309	199.67	391.40
8	3419	199.39	390.90
9	678	197.89	388.20
10	2537	197.94	388.30
11	1888	193.83	380.90
12	583	198.11	388.60
13	3001	199.33	390.80
14	3148	199.00	390.20
15	7533	200.50	392.90
16	7377	200.78	393.40
17	7371	199.06	390.30
18	6942	198.78	389.80
19	6267	199.22	390.60
20	6121	200.06	392.10
21	6001	199.89	391.80
22	15481	199.44	391.00
23	16630	198.83	389.90
24	16694	198.56	389.40
25	17804	185.33	365.60
26	11128	187.00	368.60
27	9785	197.72	387.90
28	9571	198.11	388.60
29	8197	199.00	390.20
30	15451	102.56	216.60
31	15961	99.06	210.30
32	17022	97.33	207.20
33	17551	93.22	199.80
34	10798	95.33	203.60
35	9900	71.44	160.60
36	8673	49.94	121.90
37	8225	48.22	118.80

Maximum Component Temperatures

Component	Node_1	Node_2	Node	Max_Temp(C)	Max_Temp(F)
Outside Shell	101	2894	1117	2.1633E+02	4.2140E+02
Bottom Plate	3001	3232	3120	2.0006E+02	3.9210E+02
Lid	3233	3424	3233	1.9978E+02	3.9160E+02
Shell Cavity	4001	4998	4522	2.1717E+02	4.2290E+02
Plug	5001	5404	5001	2.0489E+02	4.0080E+02
Tungsten	6001	7656	6440	2.1522E+02	4.1940E+02
LAST-A-FOAM	8001	18462	18017	3.3217E+02	6.2990E+02

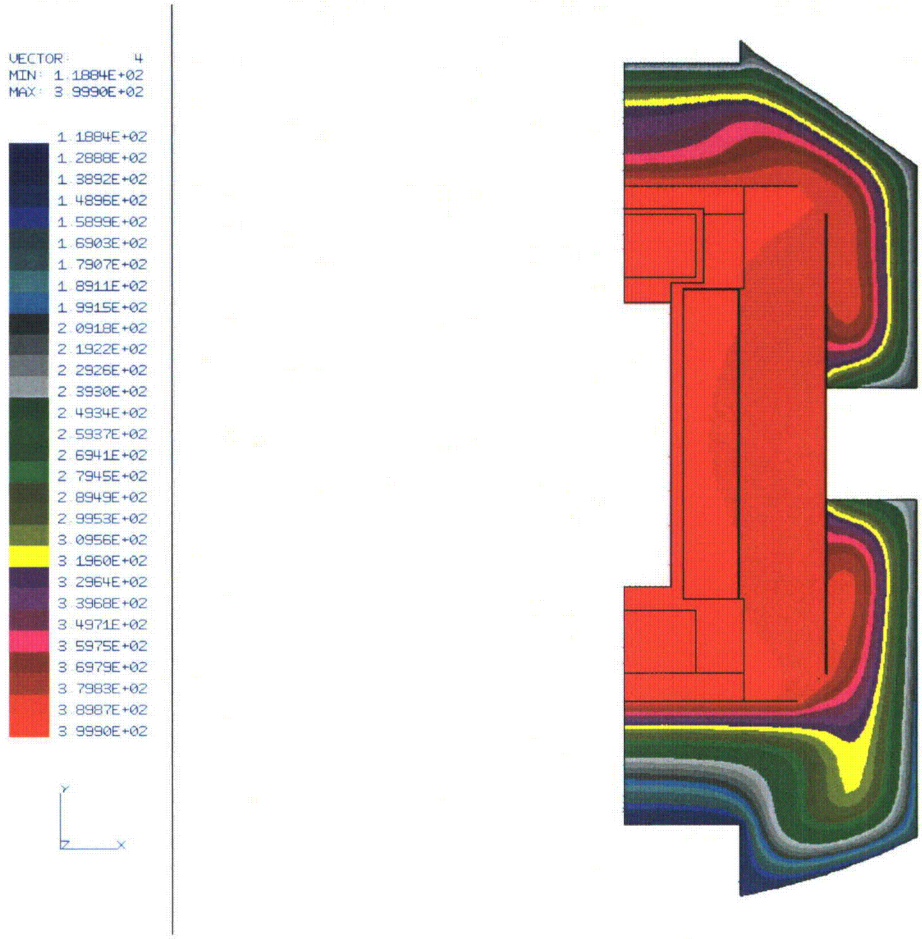

Figure 3-114. Load Case 115 – Fire at 150 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Entire Model – Model AOS-050

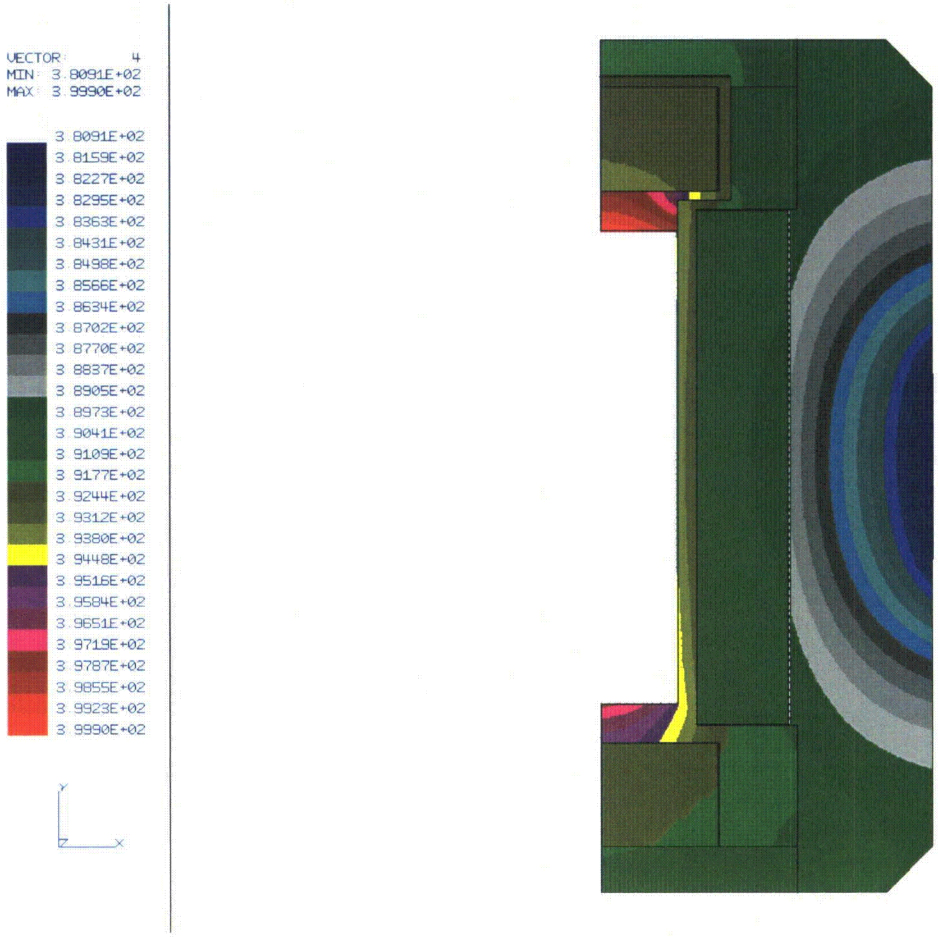

Figure 3-115. Load Case 115 – Fire at 150 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Cask Model – Model AOS-050

Table 3-87. Load Case 116 – Fire at 180 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation – Model AOS-050

Location	Node	Temp(C)	Temp(F)
1	5001	203.17	397.70
2	4532	199.17	390.50
3	4227	201.56	394.80
4	4752	199.56	391.20
5	4838	197.61	387.70
6	4995	198.06	388.50
7	3309	198.72	389.70
8	3419	198.22	388.80
9	678	196.17	385.10
10	2537	196.33	385.40
11	1888	192.11	377.80
12	583	196.44	385.60
13	3001	198.06	388.50
14	3148	197.61	387.70
15	7533	199.44	391.00
16	7377	199.67	391.40
17	7371	197.44	387.40
18	6942	197.11	386.80
19	6267	197.56	387.60
20	6121	198.61	389.50
21	6001	198.44	389.20
22	15481	198.56	389.40
23	16630	197.28	387.10
24	16694	196.67	386.00
25	17804	182.83	361.10
26	11128	184.67	364.40
27	9785	195.94	384.70
28	9571	196.67	386.00
29	8197	197.78	388.00
30	15451	100.94	213.70
31	15961	97.67	207.80
32	17022	95.17	203.30
33	17551	90.28	194.50
34	10798	93.00	199.40
35	9900	68.39	155.10
36	8673	47.50	117.50
37	8225	46.89	116.40

Maximum Component Temperatures

Component	Node_1	Node_2	Node	Max_Temp(C)	Max_Temp(F)
Outside Shell	101	2894	1117	2.1633E+02	4.2140E+02
Bottom Plate	3001	3232	3120	2.0006E+02	3.9210E+02
Lid	3233	3424	3233	1.9978E+02	3.9160E+02
Shell Cavity	4001	4998	4522	2.1717E+02	4.2290E+02
Plug	5001	5404	5001	2.0489E+02	4.0080E+02
Tungsten	6001	7656	6440	2.1522E+02	4.1940E+02
LAST-A-FOAM	8001	18462	18017	3.3217E+02	6.2990E+02

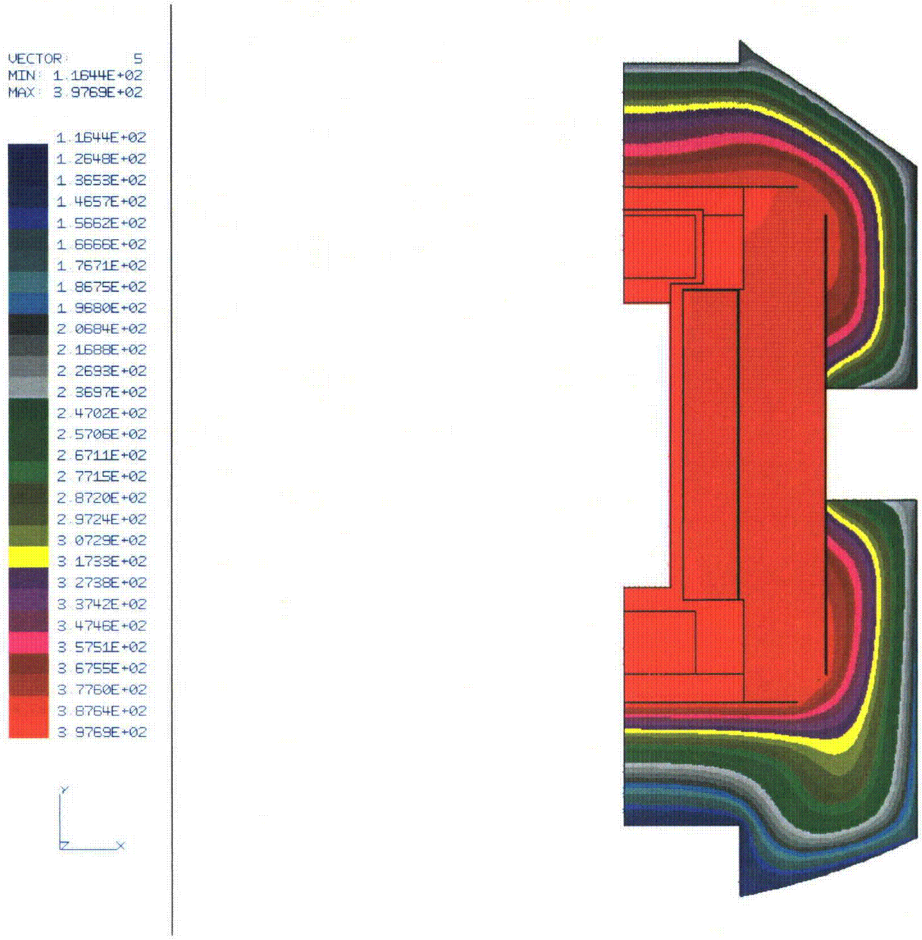

Figure 3-116. Load Case 116 – Fire at 180 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Entire Model – Model AOS-050

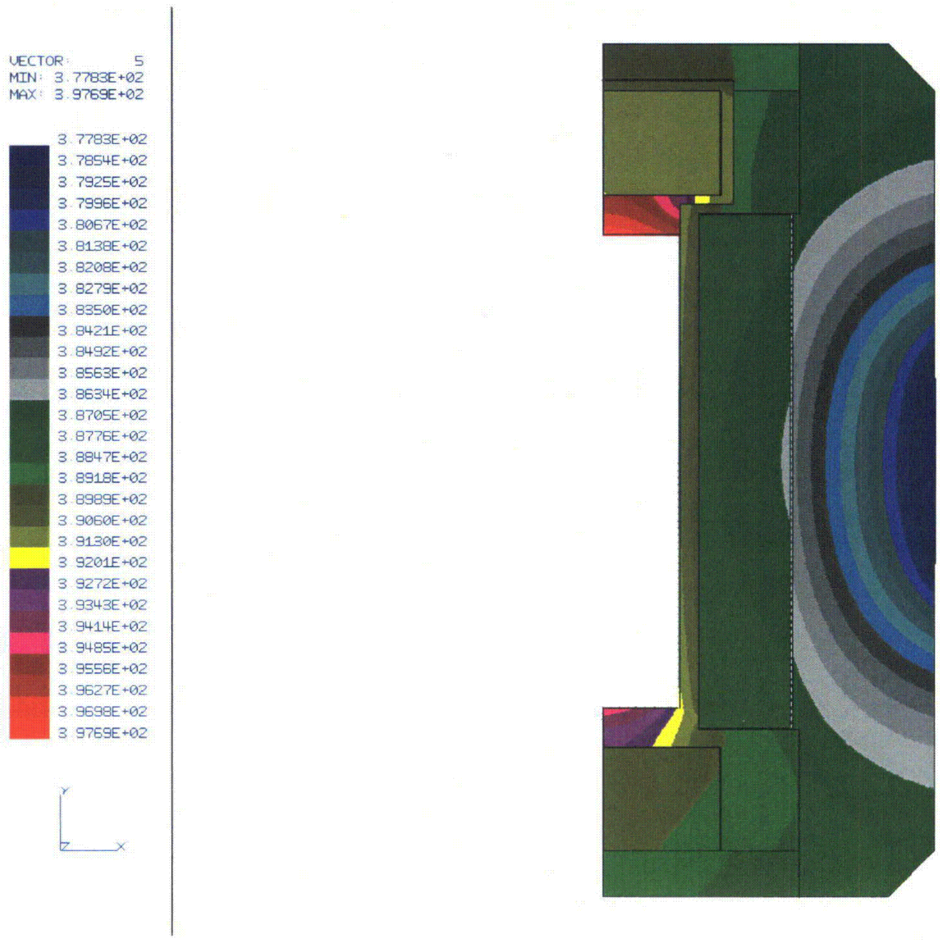

Figure 3-117. Load Case 116 – Fire at 180 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Cask Model – Model AOS-050

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3.5.2.3 Hypothetical Accident Conditions of Transport Results – Model AOS-165

Table 3-88 lists the tables and figures in this appendix that present the Model AOS-165 transport package results under Hypothetical Accident conditions of transport, for Load Cases 111 through 116. Each table provides a list of temperatures at each monitoring node. Also listed are the maximum temperatures within each transport package component.

Table 3-89 lists the temperature monitoring points (nodes) for the Model AOS-165 transport package, under Normal and Hypothetical Accident (Fire) conditions of transport. Figure 3-118 illustrates the location of each node on the transport package, under Fire conditions.

Table 3-88. Hypothetical Accident Conditions of Transport Results – Model AOS-165

Load Case	Description	Results Table	Temperature versus Time	Entire Model	Cask Model
111	Fire at 30 Minutes, 1,475°F Ambient, Maximum Decay Heat	Table 3-90	Figure 3-119	Figure 3-120	Figure 3-121
112	Fire at 60 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation	Table 3-91	–	Figure 3-122	Figure 3-123
113	Fire at 90 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation	Table 3-92	–	Figure 3-124	Figure 3-125
114	Fire at 120 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation	Table 3-93	–	Figure 3-126	Figure 3-127
115	Fire at 150 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation	Table 3-94	–	Figure 3-128	Figure 3-129
116	Fire at 180 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation	Table 3-95	–	Figure 3-130	Figure 3-131

Table 3-89. Temperature Monitoring Points, All Conditions of Transport – Model AOS-165

Nodal Location	LIBRA Model Nodal Number	
	Normal Conditions	Fire Conditions
1	5001	5001
2	4532	4532
3	4227	4227
4	4752	4752
5	4838	4838
6	4995	4995
7	3309	3309
8	3419	3419
9	678	678
10	2537	2537
11	1888	1888
12	583	583
13	3001	3001
14	3148	3148
15	7533	7533
16	7377	7377
17	7371	7371
18	6942	6942
19	6267	6267
20	6121	6121
21	6001	6001
22	9501	15481
23	9950	16630
24	10014	16694
25	10781	18111
26	9091	1153
27	8463	9785
28	8462	9571
29	8197	8197
30	9711	15451
31	9821	15961
32	10158	17032
33	10605	17743
34	9102	11051
35	8578	9900
36	8225	8673
37	8001	8225

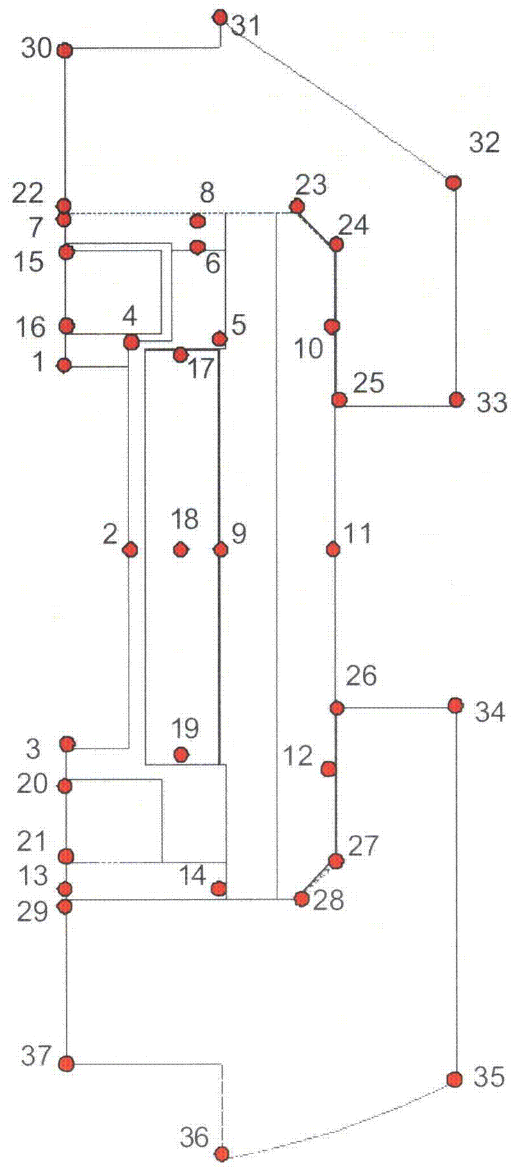

Figure 3-118. Selected Nodal Locations for Fire Conditions of Transport – Model AOS-165

Table 3-90. Load Case 111 – Fire at 30 Minutes, 1,475°F Ambient, Maximum Decay Heat – Model AOS-165

Location	Node	Temp(C)	Temp(F)
1	5001	376.56	709.80
2	4532	348.89	660.00
3	4227	363.56	686.40
4	4752	333.89	633.00
5	4838	303.44	578.20
6	4995	301.28	574.30
7	3309	308.28	586.90
8	3419	301.28	574.30
9	678	310.44	590.80
10	2537	300.39	572.70
11	1888	522.44	972.40
12	583	300.61	573.10
13	3001	307.11	584.80
14	3148	299.11	570.40
15	7533	319.83	607.70
16	7377	325.67	618.20
17	7371	312.33	594.20
18	6942	315.17	599.30
19	6267	312.61	594.70
20	6121	315.56	600.00
21	6001	310.61	591.10
22	15481	307.89	586.20
23	16630	291.61	556.90
24	16694	287.39	549.30
25	18111	652.22	1206.00
26	11531	651.11	1204.00
27	9785	289.56	553.20
28	9571	293.56	560.40
29	8197	306.83	584.30
30	15451	791.11	1456.00
31	15961	798.33	1469.00
32	17022	793.33	1460.00
33	17743	795.56	1464.00
34	11051	797.22	1467.00
35	9900	795.56	1464.00
36	8673	797.22	1467.00
37	8225	793.89	1461.00

Maximum Component Temperatures

Component	Node_1	Node_2	Node	Max_Temp(C)	Max_Temp(F)
Outside Shell	101	2894	1855	5.2244E+02	9.7240E+02
Bottom Plate	3001	3232	3120	3.0844E+02	5.8720E+02
Lid	3233	3424	3233	3.0944E+02	5.8900E+02
Shell Cavity	4001	4998	4227	3.6356E+02	6.8640E+02
Plug	5001	5404	5001	3.7656E+02	7.0980E+02
Tungsten Alloy	6001	7656	7377	3.2567E+02	6.1820E+02
LAST-A-FOAM	8001	18126	15929	7.9833E+02	1.4690E+03

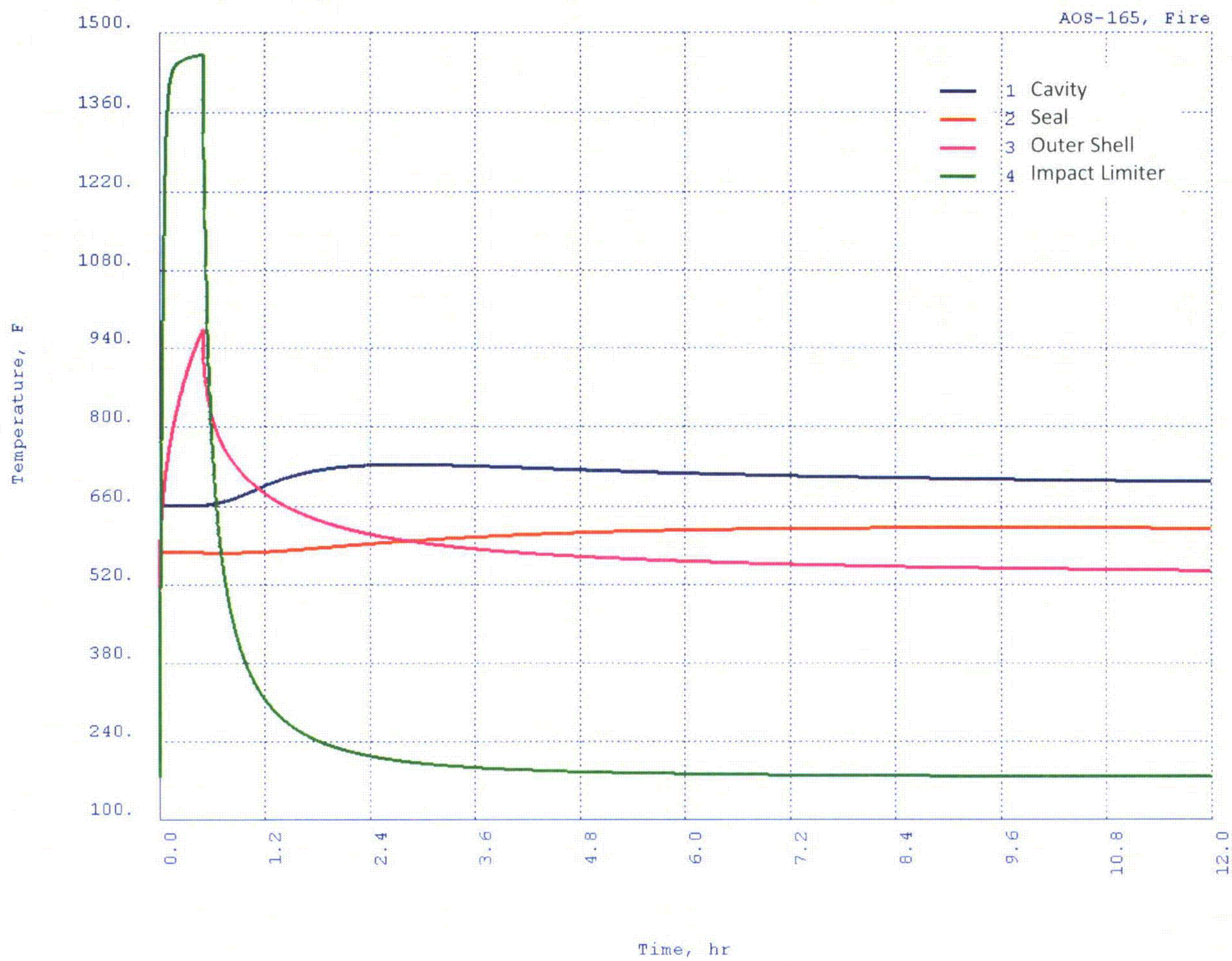

Figure 3-119. Load Case 111 – Fire at 30 Minutes, 1,475°F Ambient, Maximum Decay Heat, Temperature versus Time – Model AOS-165

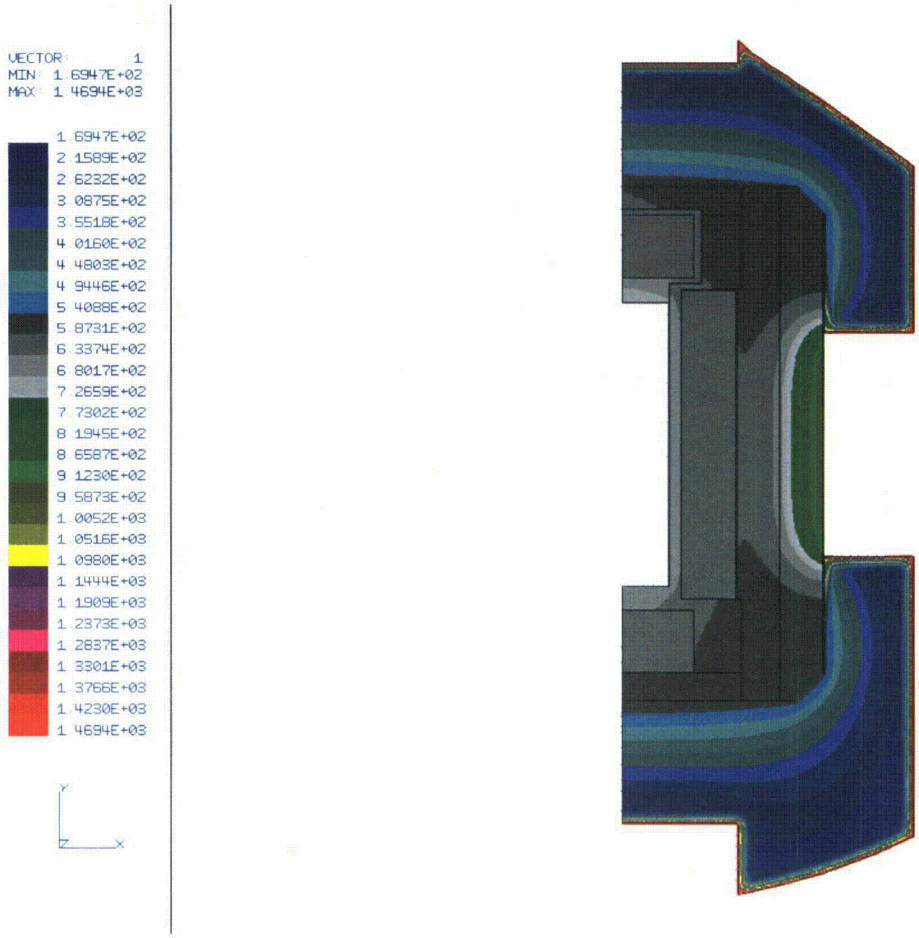

Figure 3-120. Load Case 111 – Fire at 30 Minutes, 1,475°F Ambient, Maximum Decay Heat, Entire Model – Model AOS-165

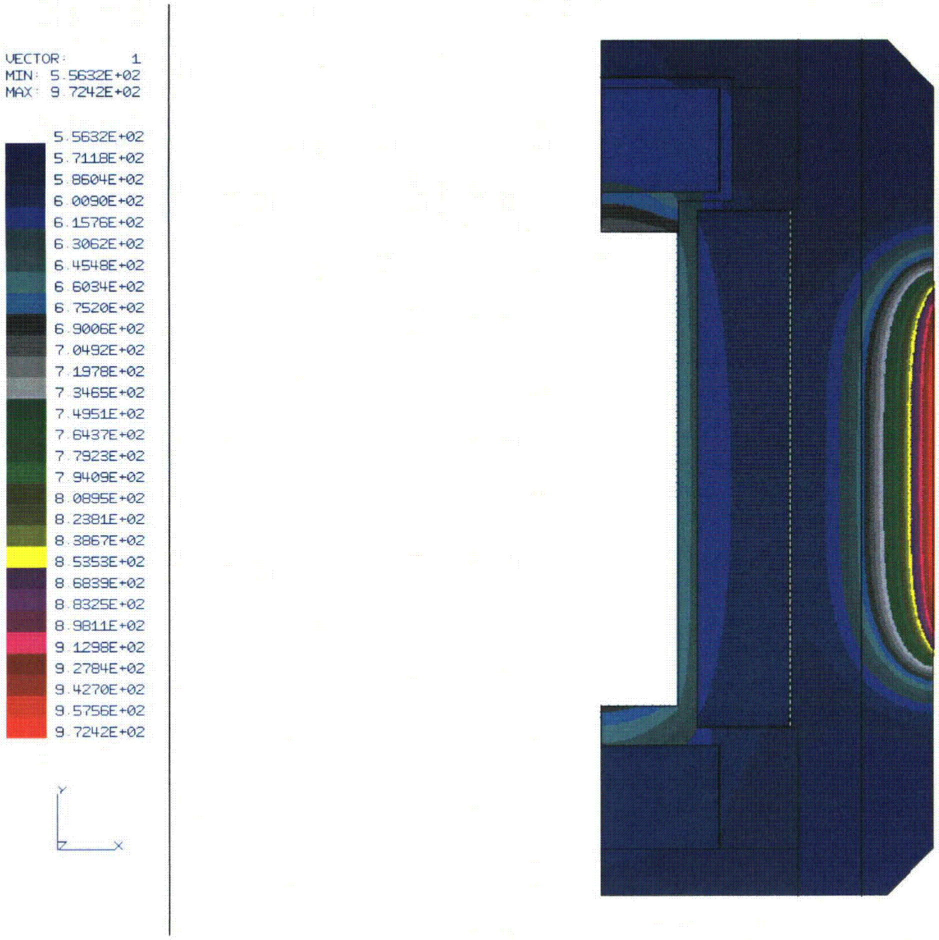

Figure 3-121. Load Case 111 – Fire at 30 Minutes, 1,475°F Ambient, Maximum Decay Heat, Cask Model – Model AOS-165

Table 3-91. Load Case 112 – Fire at 60 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation – Model AOS-165

Location	Node	Temp(C)	Temp(F)
1	5001	376.94	710.50
2	4532	360.33	680.60
3	4227	364.39	687.90
4	4752	337.00	638.60
5	4838	310.11	590.20
6	4995	301.83	575.30
7	3309	308.28	586.90
8	3419	301.39	574.50
9	678	340.89	645.60
10	2537	313.39	596.10
11	1888	374.83	706.70
12	583	313.61	596.50
13	3001	307.17	584.90
14	3148	299.50	571.10
15	7533	320.06	608.10
16	7377	325.94	618.70
17	7371	322.06	611.70
18	6942	333.00	631.40
19	6267	322.06	611.70
20	6121	316.11	601.00
21	6001	311.00	591.80
22	15481	307.89	586.20
23	16630	292.50	558.50
24	16694	289.83	553.70
25	18111	267.56	513.60
26	11531	263.94	507.10
27	9785	292.22	558.00
28	9571	294.61	562.30
29	8197	306.83	584.30
30	15451	192.56	378.60
31	15961	196.06	384.90
32	17022	188.83	371.90
33	17743	182.50	360.50
34	11051	172.78	343.00
35	9900	181.28	358.30
36	8673	194.78	382.60
37	8225	183.56	362.40

Maximum Component Temperatures

Component	Node_1	Node_2	Node	Max_Temp(C)	Max_Temp(F)
Outside Shell	101	2894	1884	3.8061E+02	7.1710E+02
Bottom Plate	3001	3232	3120	3.0856E+02	5.8740E+02
Lid	3233	3424	3233	3.0944E+02	5.8900E+02
Shell Cavity	4001	4998	4227	3.6439E+02	6.8790E+02
Plug	5001	5404	5001	3.7694E+02	7.1050E+02
Tungsten Alloy	6001	7656	6432	3.3572E+02	6.3630E+02
LAST-A-FOAM	8001	18126	15841	3.6828E+02	6.9490E+02

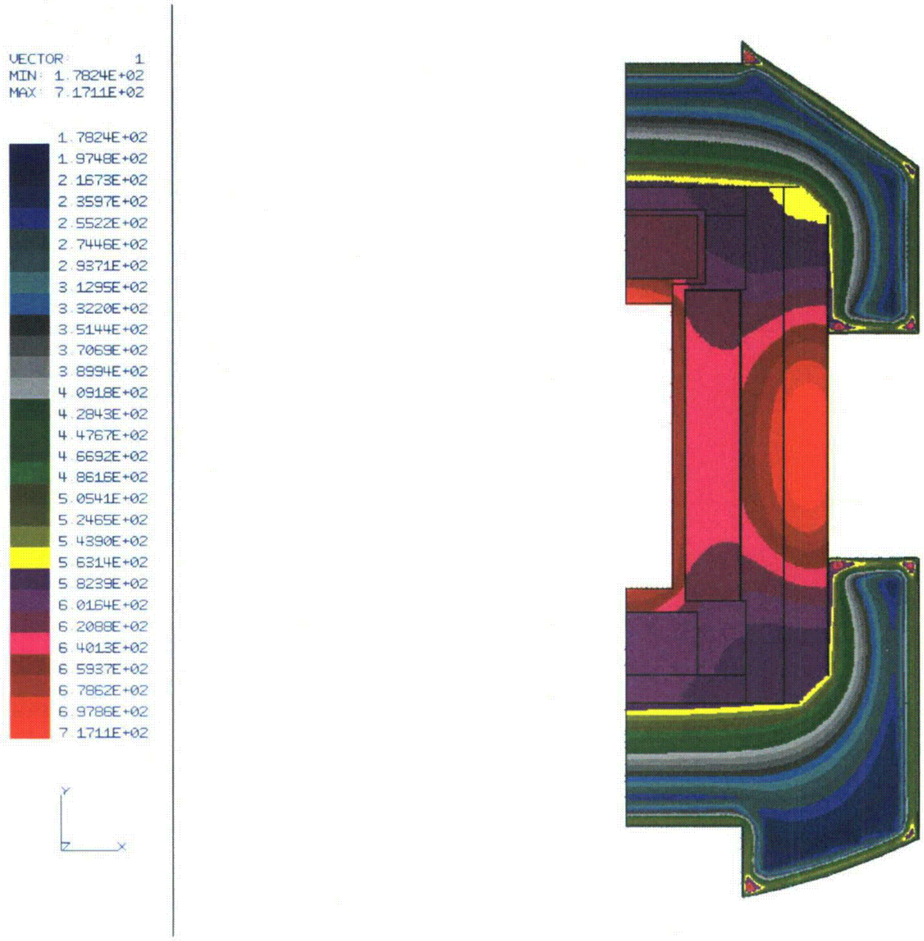

Figure 3-122. Load Case 112 – Fire at 60 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Entire Model – Model AOS-165

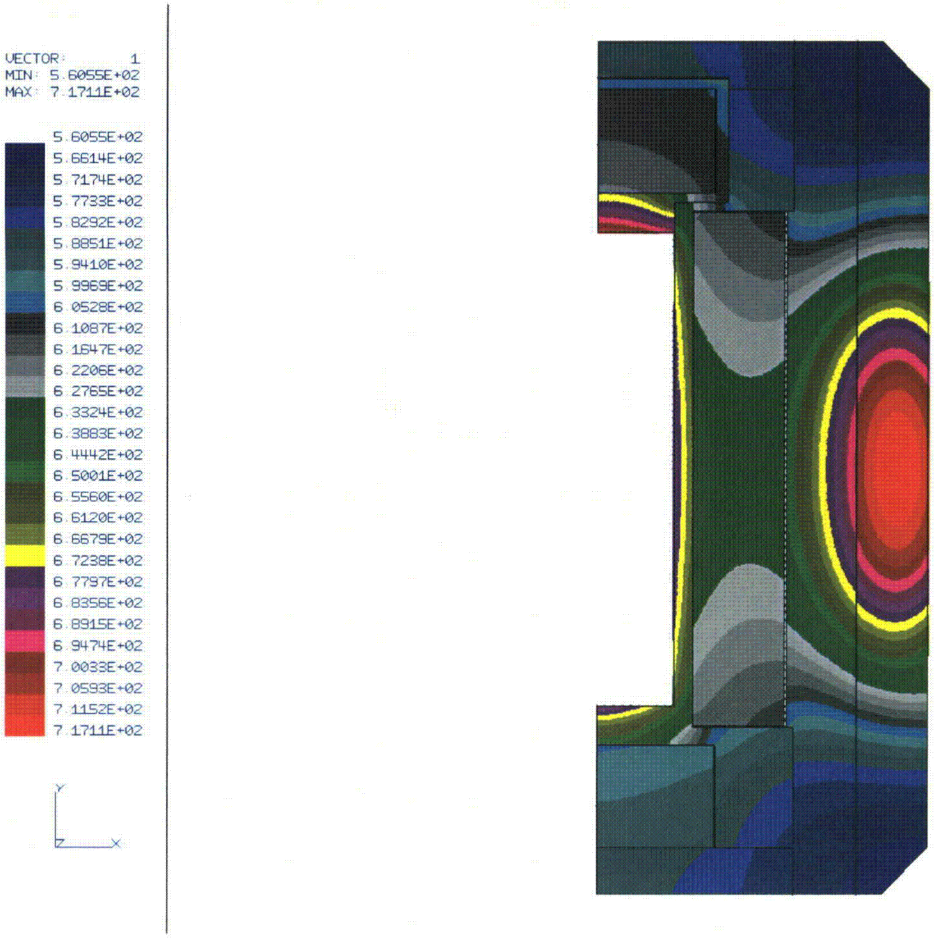

Figure 3-123. Load Case 112 – Fire at 60 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Cask Model – Model AOS-165

Table 3-92. Load Case 113 – Fire at 90 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation – Model AOS-165

Location	Node	Temp(C)	Temp(F)
1	5001	379.28	714.70
2	4532	376.56	709.80
3	4227	368.44	695.20
4	4752	343.89	651.00
5	4838	317.56	603.60
6	4995	304.22	579.60
7	3309	308.44	587.20
8	3419	302.39	576.30
9	678	349.61	661.30
10	2537	313.78	596.80
11	1888	345.22	653.40
12	583	314.50	598.10
13	3001	307.72	585.90
14	3148	301.39	574.50
15	7533	321.33	610.40
16	7377	327.61	621.70
17	7371	333.39	632.10
18	6942	347.61	657.70
19	6267	333.00	631.40
20	6121	318.94	606.10
21	6001	313.11	595.60
22	15481	308.06	586.50
23	16630	295.61	564.10
24	16694	293.83	560.90
25	18111	235.17	455.30
26	11531	233.28	451.90
27	9785	296.28	565.30
28	9571	297.89	568.20
29	8197	307.33	585.20
30	15451	129.83	265.70
31	15961	133.33	272.00
32	17022	130.61	267.10
33	17743	124.00	255.20
34	11051	116.06	240.90
35	9900	124.33	255.80
36	8673	135.11	275.20
37	8225	121.67	251.00

Maximum Component Temperatures

Component	Node_1	Node_2	Node	Max_Temp(C)	Max_Temp(F)
Outside Shell	101	2894	1884	3.8061E+02	7.1710E+02
Bottom Plate	3001	3232	3120	3.0856E+02	5.8740E+02
Lid	3233	3424	3233	3.0944E+02	5.8900E+02
Shell Cavity	4001	4998	4227	3.6439E+02	6.8790E+02
Plug	5001	5404	5001	3.7694E+02	7.1050E+02
Tungsten Alloy	6001	7656	6432	3.3572E+02	6.3630E+02
LAST-A-FOAM	8001	18126	15841	3.6828E+02	6.9490E+02

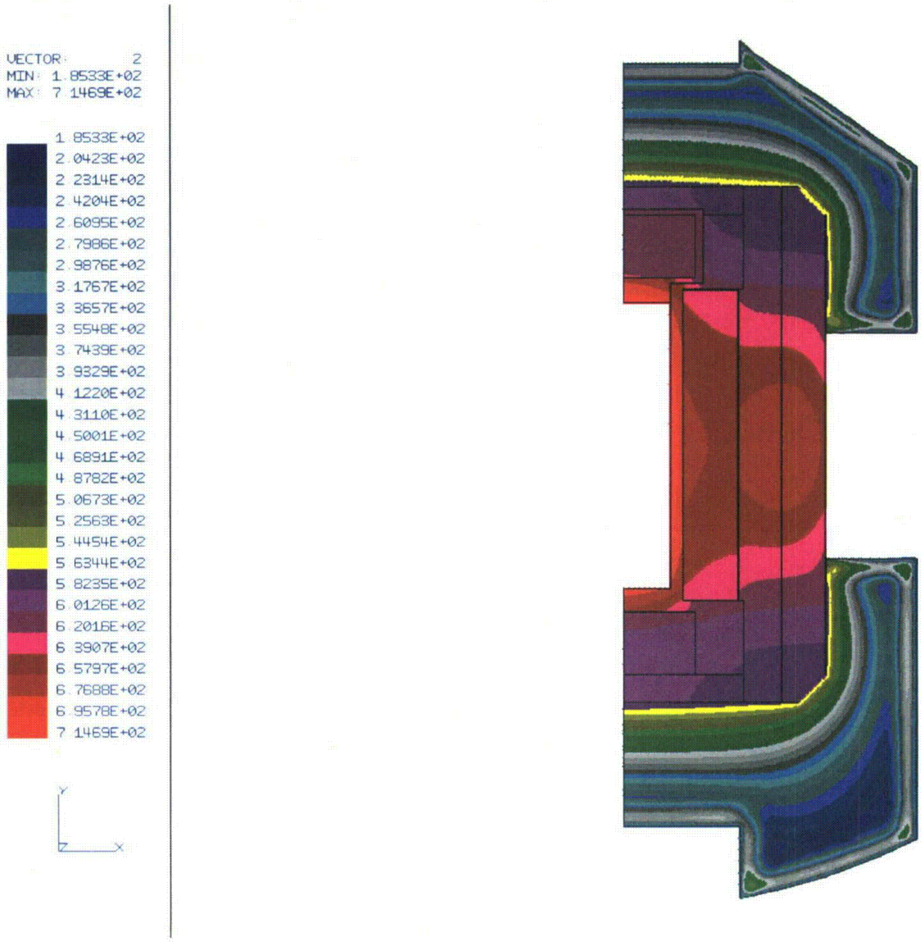

Figure 3-124. Load Case 113 – Fire at 90 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Entire Model – Model AOS-165

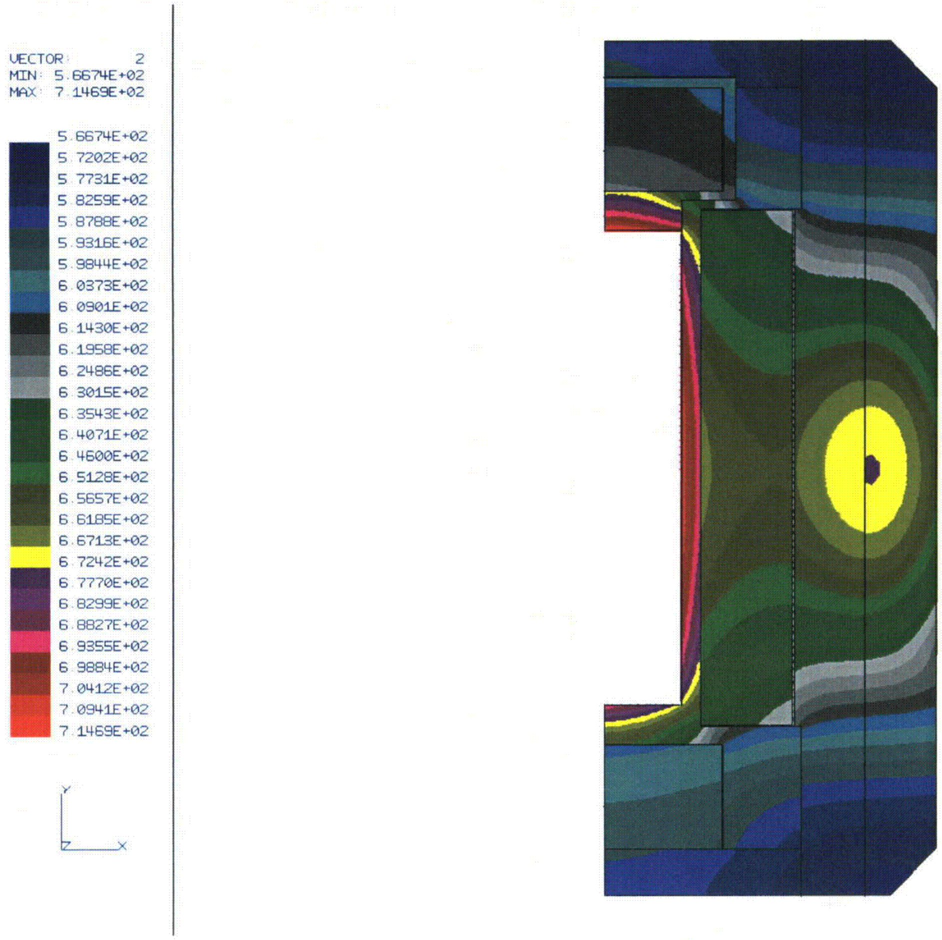

Figure 3-125. Load Case 113 – Fire at 90 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Cask Model – Model AOS-165

Table 3-93. Load Case 114 – Fire at 120 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation – Model AOS-165

Location	Node	Temp(C)	Temp(F)
1	5001	383.17	721.70
2	4532	384.94	724.90
3	4227	374.11	705.40
4	4752	349.72	661.50
5	4838	322.56	612.60
6	4995	307.67	585.80
7	3309	309.22	588.60
8	3419	304.56	580.20
9	678	349.94	661.90
10	2537	313.44	596.20
11	1888	328.78	623.80
12	583	314.33	597.80
13	3001	309.50	589.10
14	3148	304.39	579.90
15	7533	323.94	615.10
16	7377	330.61	627.10
17	7371	339.89	643.80
18	6942	353.50	668.30
19	6267	339.28	642.70
20	6121	323.17	613.70
21	6001	316.67	602.00
22	15481	308.78	587.80
23	16630	299.33	570.80
24	16694	297.39	567.30
25	18111	223.78	434.80
26	11531	222.72	432.90
27	9785	299.83	571.70
28	9571	301.61	574.90
29	8197	309.00	588.20
30	15451	105.33	221.60
31	15961	109.50	229.10
32	17022	109.22	228.60
33	17743	102.78	217.00
34	11051	96.72	206.10
35	9900	104.28	219.70
36	8673	113.22	235.80
37	8225	98.83	209.90

Maximum Component Temperatures

Component	Node_1	Node_2	Node	Max_Temp(C)	Max_Temp(F)
Outside Shell	101	2894	1884	3.8061E+02	7.1710E+02
Bottom Plate	3001	3232	3120	3.0856E+02	5.8740E+02
Lid	3233	3424	3233	3.0944E+02	5.8900E+02
Shell Cavity	4001	4998	4227	3.6439E+02	6.8790E+02
Plug	5001	5404	5001	3.7694E+02	7.1050E+02
Tungsten Alloy	6001	7656	6432	3.3572E+02	6.3630E+02
LAST-A-FOAM	8001	18126	15841	3.6828E+02	6.9490E+02

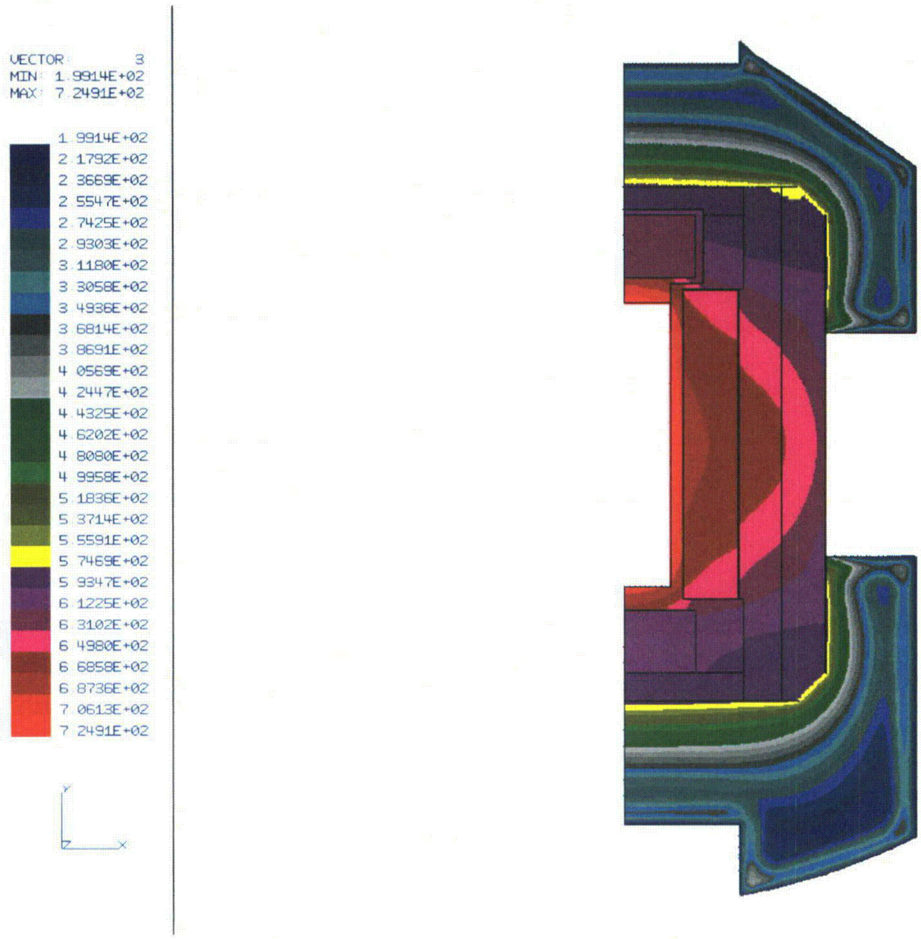

Figure 3-126. Load Case 114 – Fire at 120 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Entire Model – Model AOS-165

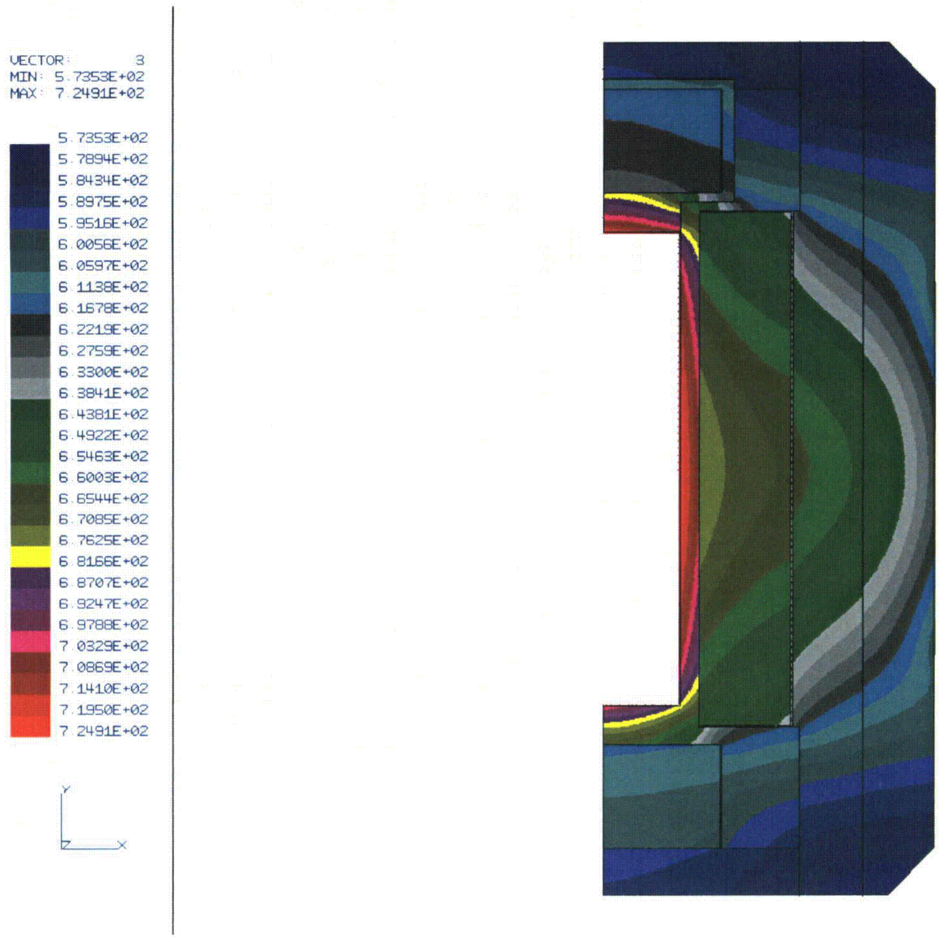

Figure 3-127. Load Case 114 – Fire at 120 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Cask Model – Model AOS-165

Table 3-94. Load Case 115 – Fire at 150 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation – Model AOS-165

Location	Node	Temp(C)	Temp(F)
1	5001	387.06	728.70
2	4532	387.78	730.00
3	4227	378.94	714.10
4	4752	353.61	668.50
5	4838	325.61	618.10
6	4995	311.17	592.10
7	3309	310.94	591.70
8	3419	307.39	585.30
9	678	348.00	658.40
10	2537	313.17	595.70
11	1888	318.39	605.10
12	583	314.22	597.60
13	3001	312.39	594.30
14	3148	307.61	585.70
15	7533	327.11	620.80
16	7377	334.00	633.20
17	7371	342.89	649.20
18	6942	354.94	670.90
19	6267	342.28	648.10
20	6121	327.28	621.10
21	6001	320.50	608.90
22	15481	310.44	590.80
23	16630	302.61	576.70
24	16694	300.22	572.40
25	18111	218.06	424.50
26	11531	217.50	423.50
27	9785	302.67	576.80
28	9571	304.89	580.80
29	8197	311.78	593.20
30	15451	93.33	200.00
31	15961	98.06	208.50
32	17022	98.94	210.10
33	17743	92.67	198.80
34	11051	87.89	190.20
35	9900	95.00	203.00
36	8673	102.78	217.00
37	8225	88.11	190.60

Maximum Component Temperatures

Component	Node_1	Node_2	Node	Max_Temp(C)	Max_Temp(F)
Outside Shell	101	2894	1884	3.8061E+02	7.1710E+02
Bottom Plate	3001	3232	3120	3.0856E+02	5.8740E+02
Lid	3233	3424	3233	3.0944E+02	5.8900E+02
Shell Cavity	4001	4998	4227	3.6439E+02	6.8790E+02
Plug	5001	5404	5001	3.7694E+02	7.1050E+02
Tungsten Alloy	6001	7656	6432	3.3572E+02	6.3630E+02
LAST-A-FOAM	8001	18126	15841	3.6828E+02	6.9490E+02

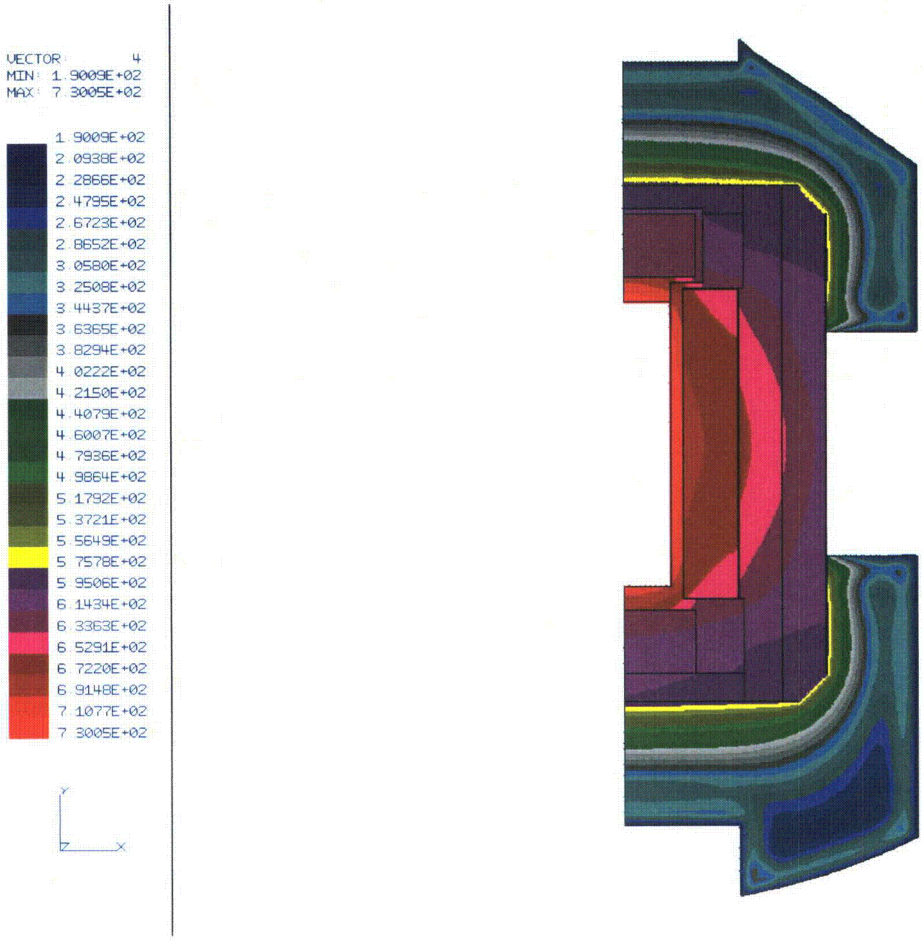

Figure 3-128. Load Case 115 – Fire at 150 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Entire Model – Model AOS-165

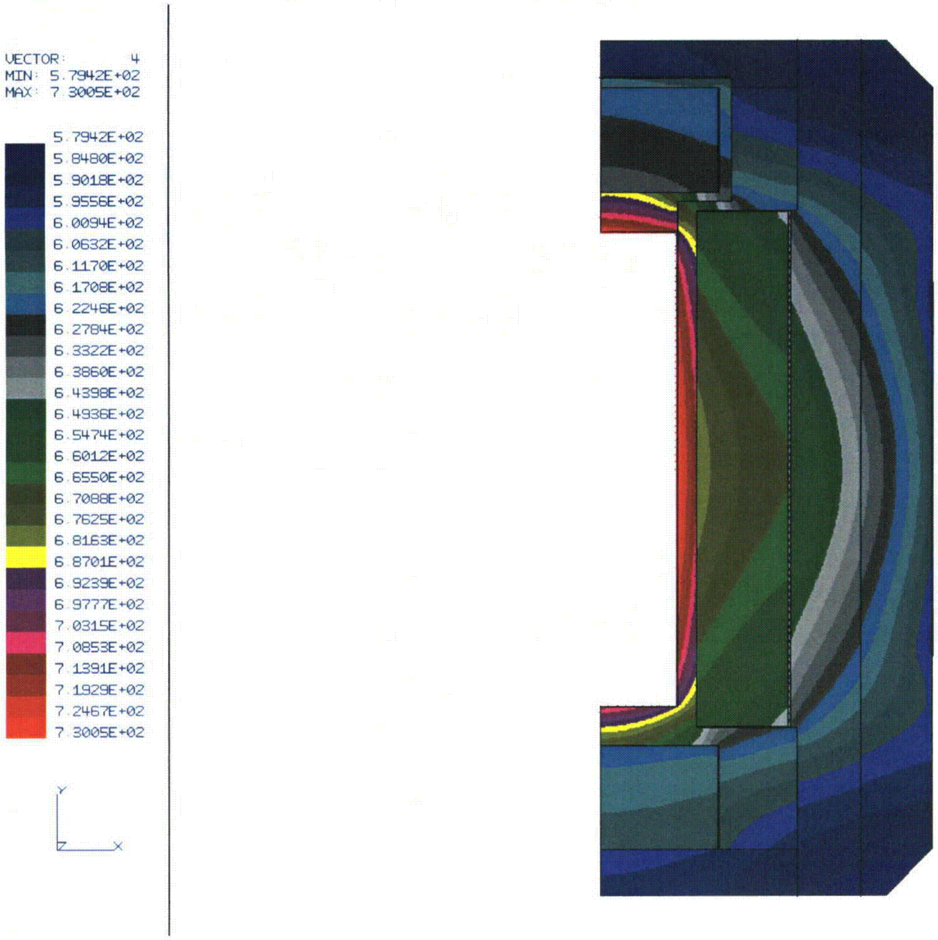

Figure 3-129. Load Case 115 – Fire at 150 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Cask Model – Model AOS-165

Table 3-95. Load Case 116 – Fire at 180 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation – Model AOS-165

Location	Node	Temp(C)	Temp(F)
1	5001	390.33	734.60
2	4532	387.94	730.30
3	4227	382.50	720.50
4	4752	356.11	673.00
5	4838	327.44	621.40
6	4995	314.22	597.60
7	3309	313.33	596.00
8	3419	310.33	590.60
9	678	345.39	653.70
10	2537	313.11	595.60
11	1888	311.28	592.30
12	583	314.22	597.60
13	3001	315.67	600.20
14	3148	310.72	591.30
15	7533	330.28	626.50
16	7377	337.22	639.00
17	7371	344.00	651.20
18	6942	354.33	669.80
19	6267	343.44	650.20
20	6121	330.78	627.40
21	6001	324.00	615.20
22	15481	312.78	595.00
23	16630	305.33	581.60
24	16694	302.61	576.70
25	18111	214.67	418.40
26	11531	214.39	417.90
27	9785	304.94	580.90
28	9571	307.61	585.70
29	8197	315.00	599.00
30	15451	86.50	187.70
31	15961	91.78	197.20
32	17022	93.22	199.80
33	17743	87.00	188.60
34	11051	83.17	181.70
35	9900	90.00	194.00
36	8673	97.00	206.60
37	8225	82.17	179.90

Maximum Component Temperatures

Component	Node_1	Node_2	Node	Max_Temp(C)	Max_Temp(F)
Outside Shell	101	2894	1884	3.8061E+02	7.1710E+02
Bottom Plate	3001	3232	3120	3.0856E+02	5.8740E+02
Lid	3233	3424	3233	3.0944E+02	5.8900E+02
Shell Cavity	4001	4998	4227	3.6439E+02	6.8790E+02
Plug	5001	5404	5001	3.7694E+02	7.1050E+02
Tungsten Alloy	6001	7656	6432	3.3572E+02	6.3630E+02
LAST-A-FOAM	8001	18126	15841	3.6828E+02	6.9490E+02

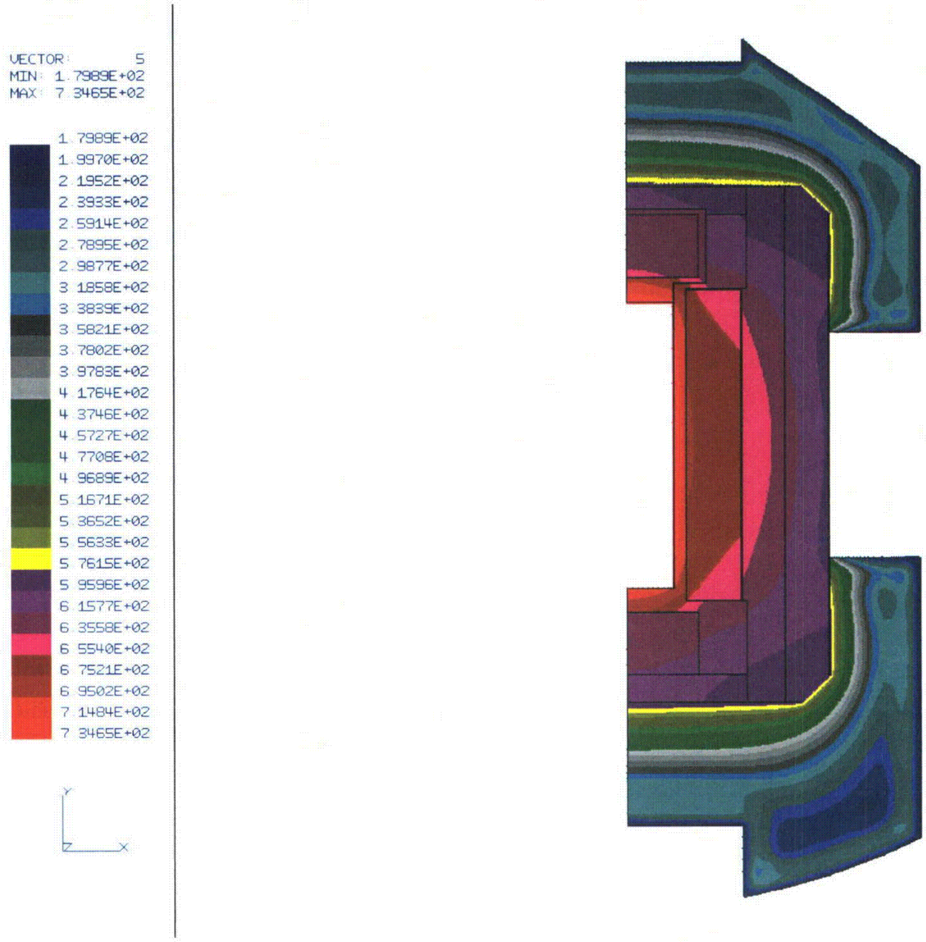

Figure 3-130. Load Case 116 – Fire at 180 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Entire Model – Model AOS-165

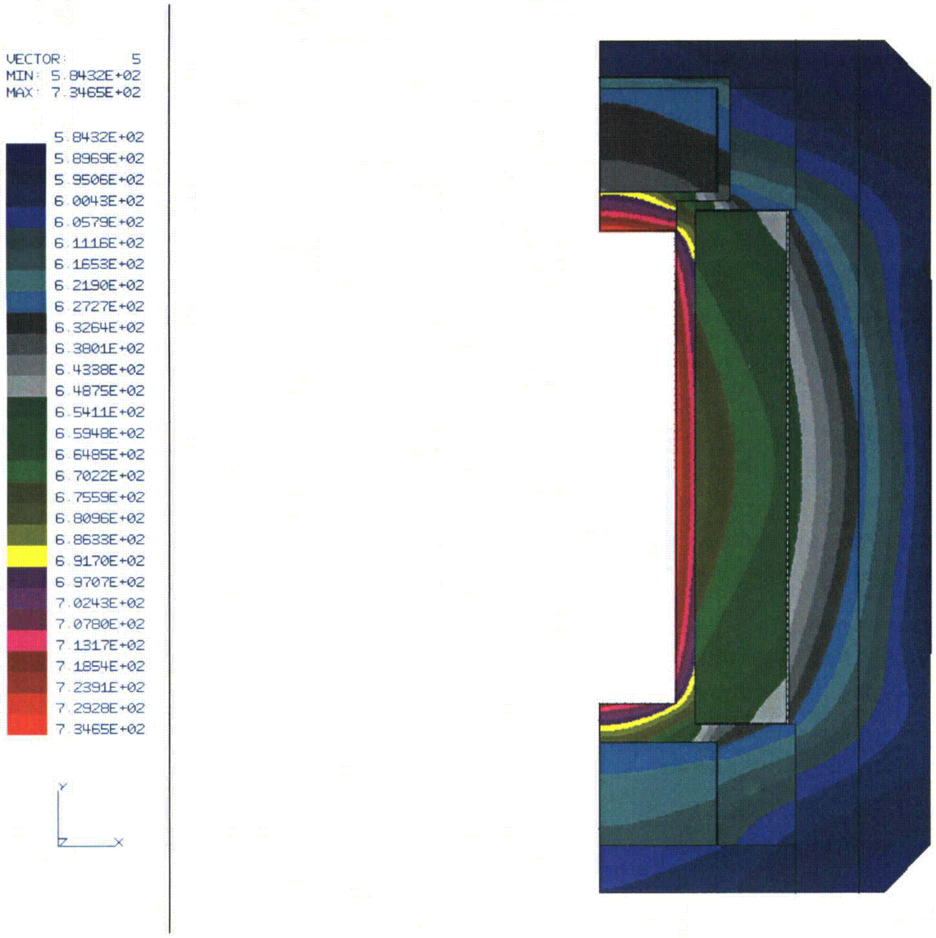

Figure 3-131. Load Case 116 – Fire at 180 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Cask Model – Model AOS-165

3.5.3 LIBRA Finite Element Program Heat Transfer Module

3.5.3.1 Description of the LIBRA Heat Transfer Program

The LIBRA heat transfer program performs steady-state and transient analyses of two- and three-dimensional structures. The LIBRA heat transfer code is compatible with the structural code in that essentially the same model can be used for both structural and thermal analyses, and temperature fields determined in thermal analyses can be saved and applied in subsequent structural analyses.

For transient thermal problems the user can control the integration scheme by specifying the integration parameter. A zero (0) value of this parameter gives an explicit integration scheme, while values between zero (0) and one (1) give implicit schemes. Usually, a value of one (1) for the integration parameter was used, and this value corresponds to a backward difference integration technique.

The LIBRA user can specify property changes at user-directed intervals in transient problems. At such times, the LIBRA code passes control to a user-written subroutine, which allows the introduction of temperature-dependent properties. This program feature was widely used in the analysis of the transport package.

3.5.3.2 Qualification and Verification of LIBRA Program

To assess the accuracy of the LIBRA computer program, a qualification and verification program was conducted. The program included verification against exact solution type of problems and benchmarking in the thermal area. The GE Model 2000 heat tests were performed to verify thermal properties used in the analytical model, In particular, the Model 2000 heat tests were used to validate thermal conduction properties for cask structural and shielding materials. The LIBRA program accuracy is demonstrated by a number of verification problems, described below, and by tests applied to the Model AOS-165A transport package.

3.5.3.3 Heat Transfer Problems with Exact Solution

Six example problems were solved analytically and by application of the LIBRA heat transfer program. The problems solved included plane and axisymmetric (2D) geometry and involved convective, radiative, and fixed temperature boundary conditions. In all problems solved, both steady-state and transient problems, agreement between the analytical solutions and the LIBRA program was within 1%. Table 3-96 summarizes these problems and the comparison of results.

3.5.3.4 Heat Transfer Benchmarking Test

A thermal test was performed on a GE Model 2000 transport package. The content heat load was simulated by electric heaters. Thermocouples were placed at strategic locations:

- Inside the cask cavity,
- On the outside cask surface,
- On the inside overpack surfaces, and
- Exterior to overpack structure.

Temperatures were periodically recorded as the heater power was varied from 0 to 3 kW. Steady-state temperatures were recorded for various heater powers from 1 to 3 kW.

A finite element model of the package was developed and was applied to a thermal analysis using the LIBRA Heat Transfer Program. A comparison of heat test (HT) and LIBRA results are provided in Table 3-97.

A more detailed description of the GE Model 2000 heat tests is provided in Appendix 3.5.3.5.

Table 3-96. Summary of Heat Transfer Exact Solution Properties and their Results

Problem Type	Problem Statement	Theory	LIBRA	References
Transient conduction	Concrete wall at initial temperature (Ti), suddenly exposed on one side to hot gas at (Tg).	X L T(°F) 0.000 508.8 0.167 538.2 0.333 625.3 0.500 766.3 0.667 954.7 0.833 1,180.7 1.000 1,431.8	T(°F) 507 535 622 763 952 1,180 1,430	Kreith, Frank, *Principles of Heat Transfer*, International Textbook Company, Pennsylvania, 2nd Ed., 1969, Example 4-4.
Steady-state conduction	Concrete slab has its two surfaces maintained at T_1 and T_2. Obtain heat transfer rate.	120 Btu/h-ft^2	120 Btu/h-ft^2	Gebhart, Benjamin, *Heat Transfer*, The McGraw-Hill Companies, New York, 2nd Ed., 1971, Example 2-1.
Internal heat generation/ steady-state	A uniformly heat-generating plate of thickness t, subjected to a temperature T_1 on inside and T_2 on the other side.	X L T(°F) 0.000 141 0.125 330 0.250 471 0.375 562 0.500 605 0.625 599 0.750 544 0.875 440 1.000 288	T(°F) 142 331 471 562 605 599 544 440 287	Garret, J. K., *THTD Verification Manual*, General Electric Company, San Jose, CA, 1980.
Conduction with radiation and convection boundaries	A plate has a heat flux on one side, and the other side radiates to two sinks.	Surface Temperature 659.7°F	Surface Temperature 659.7°F	Ibid.
Axisymmetric (2D), transient conduction	An infinitely long rod of radius R having a uniform initial temperature T~ is plunged suddenly into a bath at T_∞.	r/R T(°F) 0.8 6.6 0.1 87.0 0.2 87.6 0.3 88.5 0.4 89.7 0.5 91.2 0.6 92.8 0.7 94.6 0.8 96.5 0.9 98.3 1.0 100.0	T(°F) 86.6 87.0 87.6 88.5 89.7 91.2 92.9 94.7 96.5 98.3 100.0	

Table 3-96. Summary of Heat Transfer Exact Solution Properties and their Results (Continued)

Problem Type	Problem Statement	Theory		LIBRA	References
Axisymmetric (2D), transient conduction with convective boundary	A rod having a uniform initial temperature Ti is quenched in an oil bath at T∞.	r/R	T(°F)	T(°F)	Ibid, Example 5-13.
		0	490.0	490	
		0.1	489.0	488	
		0.2	485.7	485	
		0.3	480.2	479	
		0.4	472.6	472	
		0.5	462.9	462	
		0.6	451.3	450	
		0.7	437.8	437	
		0.8	422.5	421	
		0.9	405.6	404	
		1.0	387.2	386	

Table 3-97. Comparison of Heat Test GE Model 2000 and LIBRA Results

Location	p = 1.1 kW		p = 2 kW		p = 3 kW	
	HT (°F)	LIBRA (°F)	HT (°F)	LIBRA (°F)	HT (°F)	LIBRA (°F)
Cavity	264	248	395	372	527	474
Cask Surface	166	179	243	256	319	308
Inside Jacket	101	99	139	138	168	158
Outside Jacket	80	82	98	107	102	111

3.5.3.5 GE Model 2000 Heat Test Description

The GE Model 2000 heat tests were conducted outside, using a test structure only partially enclosed by plywood. In addition, tests were conducted over an extended time period, during which the ambient temperature varied by over 20°F. Consequently, test convective values could not be accurately identified. However, thermal conduction values can be evaluated without accurate convection properties, by matching test and analytical temperature patterns. To this end, approximate ambient temperature and convection values were applied in the analysis of the test event. While the approximate convection properties produced the consistently low temperature correlation, the calculated temperature patterns correlated well with test results validating the model.

The Model AOS-165A test was performed under a more controlled environment, and the correlation between analytical and test temperatures were very good. Accuracy of the LIBRA code is further demonstrated by the following eight solutions, presented in the LIBRA program verification documentation. These problems were chosen to exercise the LIBRA program elements and features used in the AOS thermal analyses. The LIBRA input models for these problems are contained on the **LIBRA** program CD, **Libra64** folder, **verification** sub-folder.

ver_prob.1 (Main 12, Elements 34 & 32)

Axisymmetric, steady-state heat transfer of Carbon resistor, graphite core and michanite conductor, model 1. Solution from Edwards, Denny, and Mills, *Transfer Processes*, 2nd Ed., p. 27 **[3.15]**.

```
graphite temperature = 368.8
Libra node 15 temperature = 368.5
```

ver_prob.2 (Main 12, Elements 34 & 32)

Axisymmetric, steady-state heat transfer of Carbon resistor, graphite core and michanite conductor, model 2. Solution from Edwards, Denny, and Mills, *Transfer Processes*, 2nd Ed., p. 27 **[3.15]**.

```
graphite temperature = 368.8
Libra node 39 temperature = 368.5
```

ver_prob.3 (Main 12, Elements 34 & 32)

Axisymmetric, steady-state heat transfer of Carbon resistor, graphite core and michanite conductor, model 3. Solution from Edwards, Denny, and Mills, *Transfer Processes*, 2nd Ed., p. 27 **[3.15]**.

```
graphite temperature = 368.8
Libra node 39 temperature = 368.5
```

ver_prob.4 (Main 12, Elements 34 & 32)

Axisymmetric, steady-state heat transfer of Carbon resistor, graphite core and michanite conductor, model 4. Solution from Edwards, Denny, and Mills, *Transfer Processes*, 2nd Ed., p. 27 **[3.15]**.

```
core temperature = 434.8
Libra node 6 temperature = 434.8
```

ver_prob.5 (Main 12, Elements 34 & 32)

Axisymmetric, transient heat transfer of copper wire initially at 300 deg immersed in water. Solution from Kreith, *Principals of Heat Transfer*, 2nd Ed., p. 131 **[3.14]**.

Item	Theory	Libra
time step 16 temp	173.7	175.2
time step 32 temp	127.1	128.3
time step 48 temp	110.0	110.6
time step 64 temp	103.7	104.0
time step 90 temp	101.4	101.5

ver_prob.6 (Main 12, Elements 34 & 32)

Axisymmetric, transient heat transfer of copper wire initially at 300 deg, immersed in air. Solution from Kreith, *Principals of Heat Transfer*, 2nd Ed., p. 131 **[3.14]**.

Item	Theory	Libra
temperature @ time step 32	217.5	217.3
temperature @ time step 64	169.0	168.8
temperature @ time step 96	140.5	140.3
temperature @ time step 128	123.8	123.7
temperature @ time step 160	114.0	113.9

ver_prob.7 (Main 12, Elements 34 & 32)

Transient heat transfer of concrete wall initially at 100 deg exposed to gas at 1,600 deg. Solution from Kreith, *Principals of Heat Transfer*, 2nd Ed., p. 151 **[3.14]**.

Item	Theory	Libra

3.5.4 Tungsten Alloy versus Carbon Steel Materials Comparison

Temperature results are presented for the Model AOS-100B transport package's cask, using tungsten alloy or carbon steel (shielding material). Table 3-98 lists the figures associated with Load Cases 102, and 111 through 115.

Notes: *Only the results are presented within this appendix.*

Results data is not included for Load Case 116.

Comparative results are shown for each shielding material with the same loading. The loading conditions evaluated are:

- 400W decay heat plus insolation
- 5-hour fire transient – 30-minute fire at 1,475°F and 4.5-hour cool down at 100°F, 400W decay heat

Table 3-98. Tungsten Alloy versus Carbon Steel Shielding Results – Models AOS-100B

Load Case	Description	Temperature versus Time	Entire Model	Cask Model
102	100°F Ambient, 400W Decay Heat, Maximum Insolation	–	Figure 3-133	Figure 3-134
111	Fire at 30 Minutes, 1,475°F Ambient, 400W Decay Heat	Figure 3-135	Figure 3-136	Figure 3-137
112	Fire at 60 Minutes, 100°F, 400W Decay Heat, Maximum Insolation	–	Figure 3-138	Figure 3-139
113	Fire at 90 Minutes, 100°F, 400W Decay Heat, Maximum Insolation	–	Figure 3-140	Figure 3-141
114	Fire at 120 Minutes, 100°F, 400W Decay Heat, Maximum Insolation	–	Figure 3-142	Figure 3-143
115	Fire at 150 Minutes, 100°F, 400W Decay Heat, Maximum Insolation	–	Figure 3-144	Figure 3-145

Table 3-99 lists the carbon steel (~ 0.5% carbon) properties used for this testing **[3.13]**.

Table 3-99. *Carbon Steel Properties*

Temperature (°C)	Conductivity (W/m-°C)	Thermal Diffusivity (m^2/hr)	Specific Heat (KJ/kg-°C)
Material: SA-105, *Carbon Steel Forging*			
21.1	60.75	0.06457	0.4324
37.8	60.06	0.06262	0.4408
65.6	59.02	0.05992	0.4527
93.3	58.15	0.05695	0.4693
121.1	56.94	0.05435	0.4815
148.9	55.90	0.05212	0.4930
204.4	53.48	0.04757	0.5167
260.0	51.06	0.04385	0.5351
315.6	48.46	0.04023	0.5537
343.3	47.25	0.03846	0.5646
371.1	46.04	0.03660	0.5780
398.9	44.83	0.03475	0.5929
426.7	43.61	0.03298	0.6078
454.4	42.40	0.03112	0.6262
482.2	41.19	0.02945	0.6483

Density = 7,832.8 kg/m^3

= 0.283 lb/in^3

The conductivity property as a function of temperature is defined as:

$$K = 3.003 - 1.027E\text{-}3\ T - 1.249E\text{-}7\ T^2$$

where:

K = Conductivity - Btu/hr-in-°F

T = Temperature - °F

The specific heat property as a function of temperature is defined as:

$$Cp = 0.1009 + 4.847E\text{-}5\ T + 9.493E\text{-}9\ T^2$$

where:

Cp = Specific heat - Btu/lb-°F

T = Temperature, °F

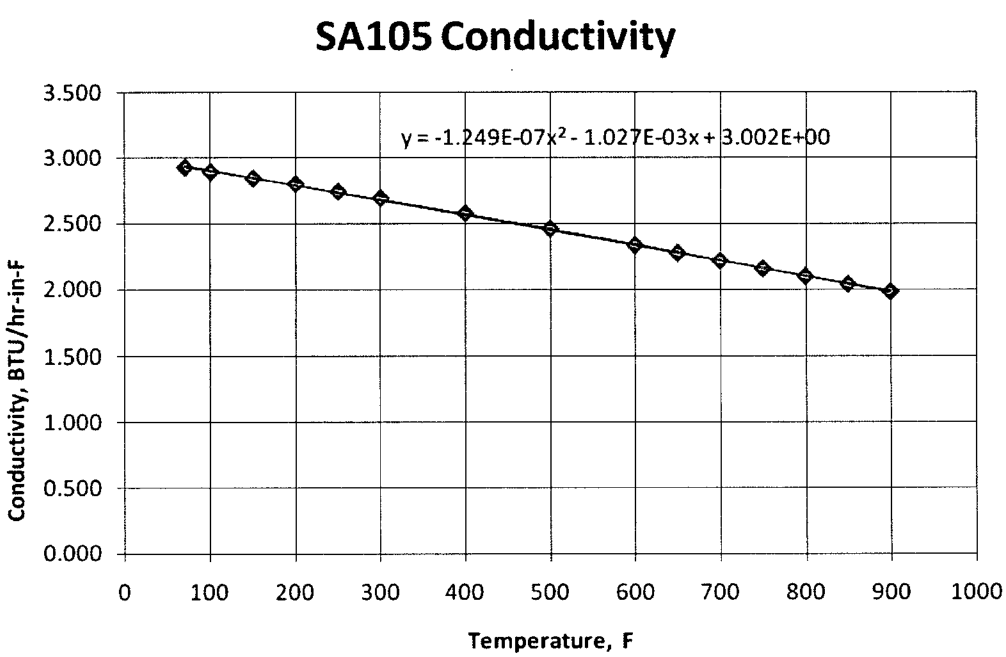

Figure 3-132. Carbon Steel Conductivity (~ 0.5% Carbon) – Model AOS-100B

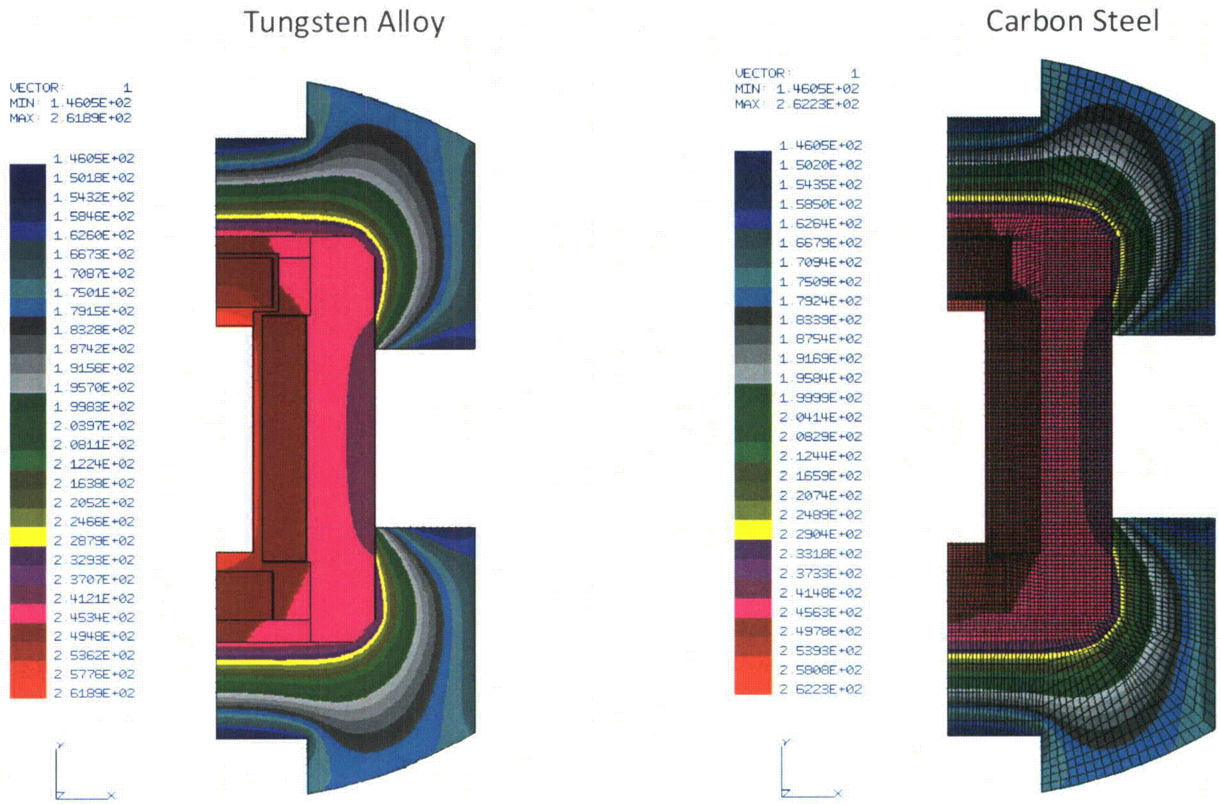

Figure 3-133. Load Case 102 – 100°F Ambient, 400W Decay Heat, Maximum Insolation, Entire Model – Tungsten Alloy (Model AOS-100A) and Carbon Steel (Model AOS-100B)

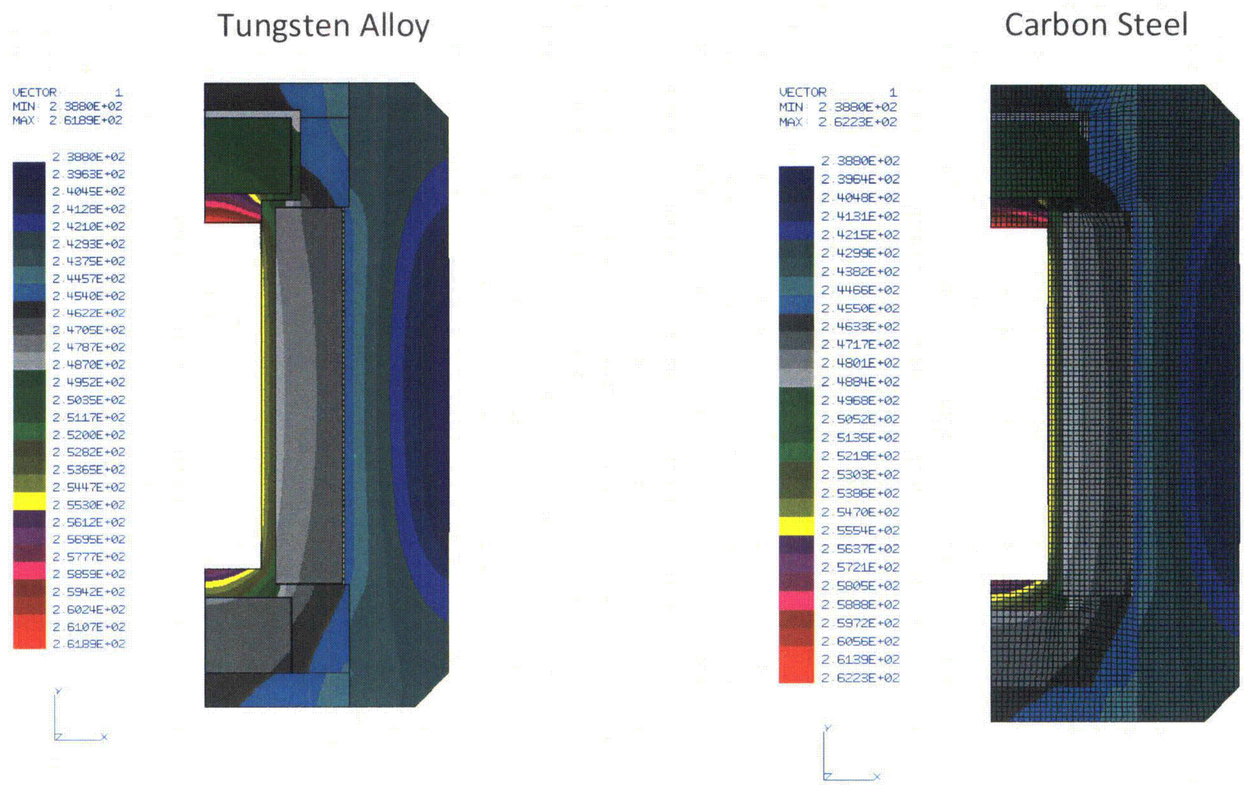

Figure 3-134. Load Case 102 – 100°F Ambient, 400W Decay Heat, Maximum Insolation, Cask Model – Tungsten Alloy (Model AOS-100A) and Carbon Steel (Model AOS-100B)

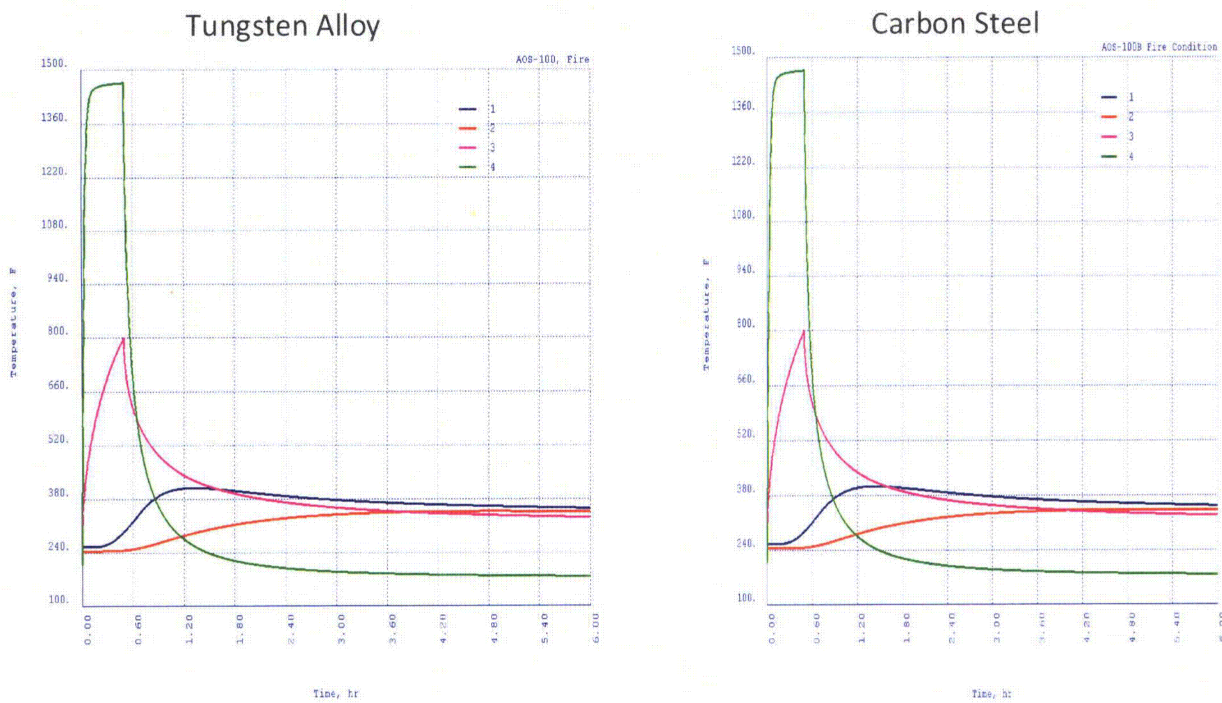

Figure 3-135. 5-Hour Fire Transient, Fire at 30 Minutes, 1,475°F Ambient, 4.5-Hour Cool Down at 100°F – Tungsten Alloy (Model AOS-100A) and Carbon Steel (Model AOS-100B)

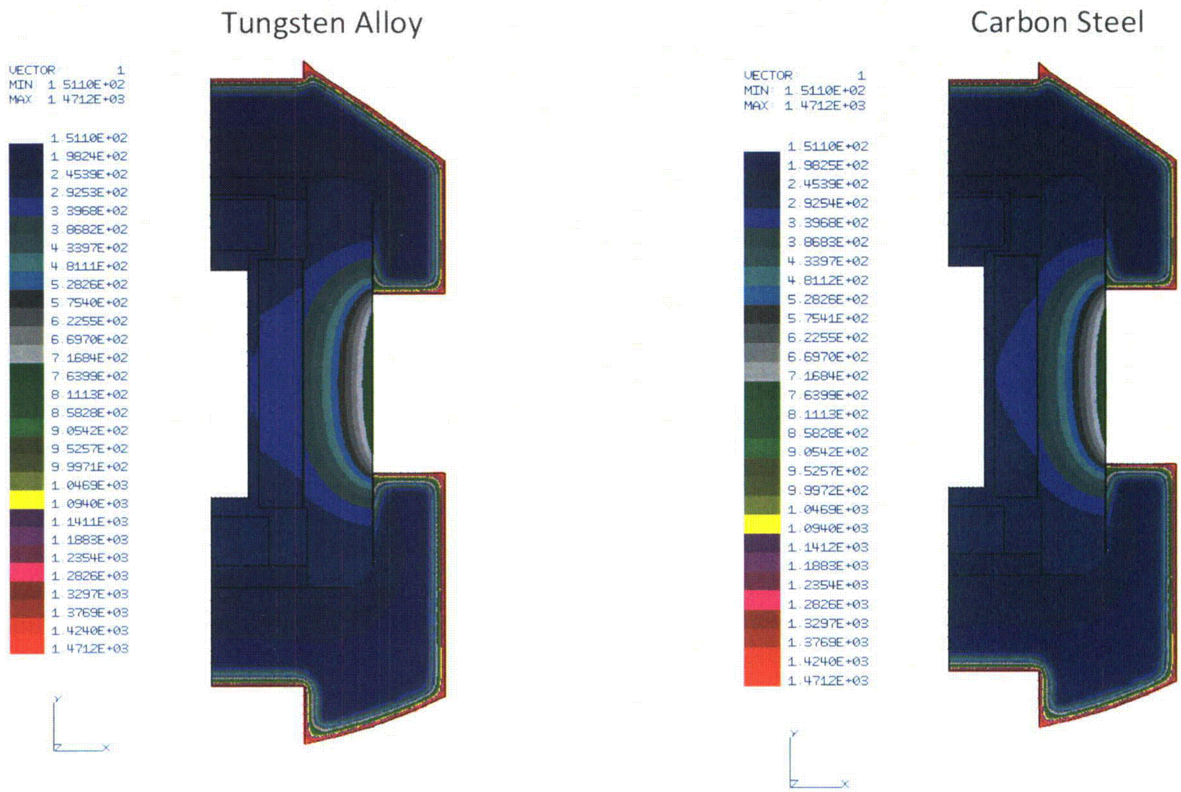

Figure 3-136. Load Case 111 – Fire at 30 Minutes, 1,475°F Ambient, 400W Decay Heat, Entire Model – Tungsten Alloy (Model AOS-100A) and Carbon Steel (Model AOS-100B)

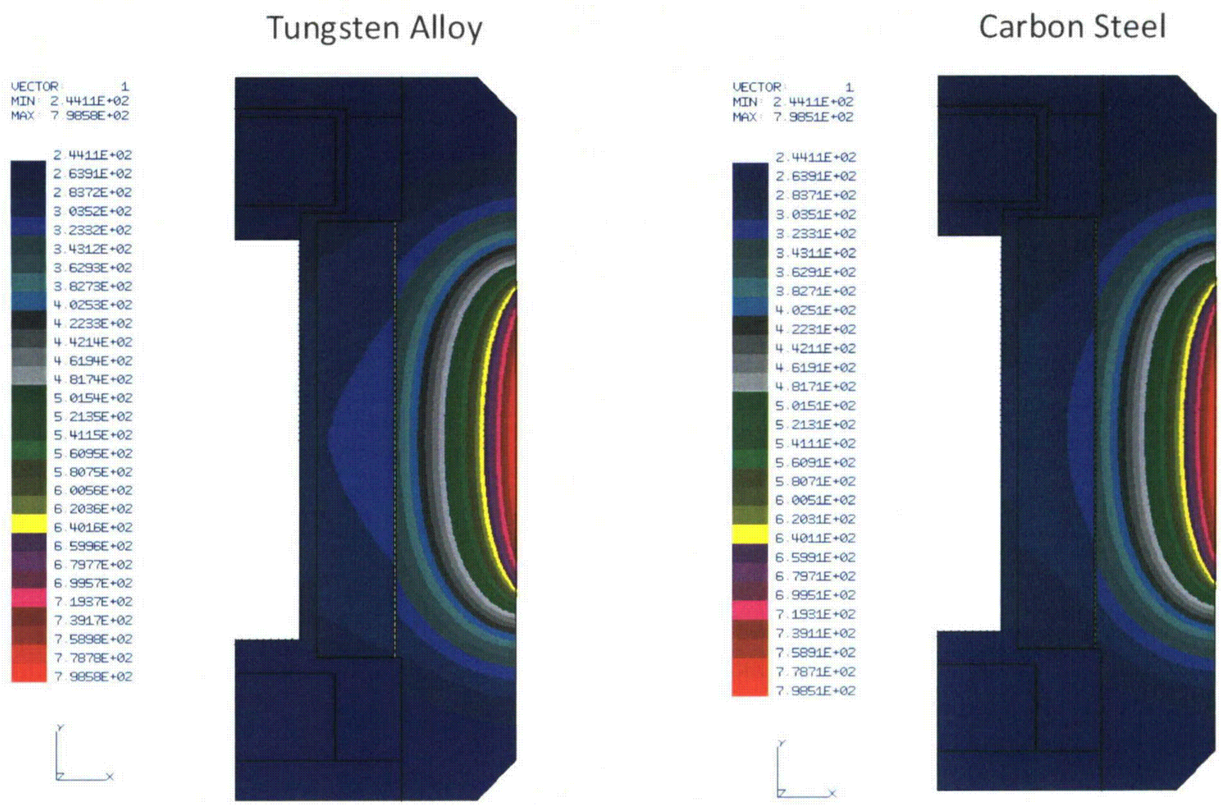

Figure 3-137. Load Case 111 – Fire at 30 Minutes, 1,475°F Ambient, 400W Decay Heat, Cask Model – Tungsten Alloy (Model AOS-100A) and Carbon Steel (Model AOS-100B)

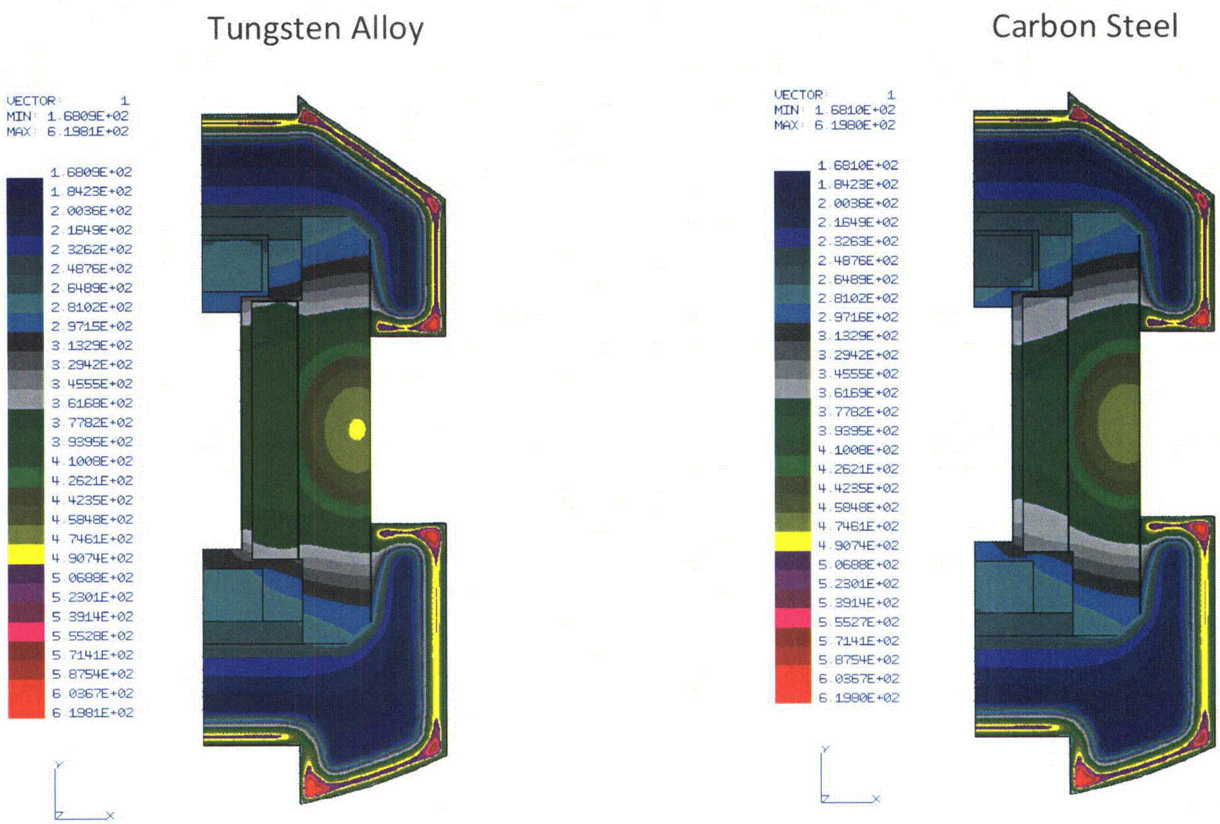

Figure 3-138. Load Case 112 – Fire at 60 Minutes, 100°F, 400W Decay Heat, Maximum Insolation, Entire Model – Tungsten Alloy (Model AOS-100A) and Carbon Steel (Model AOS-100B)

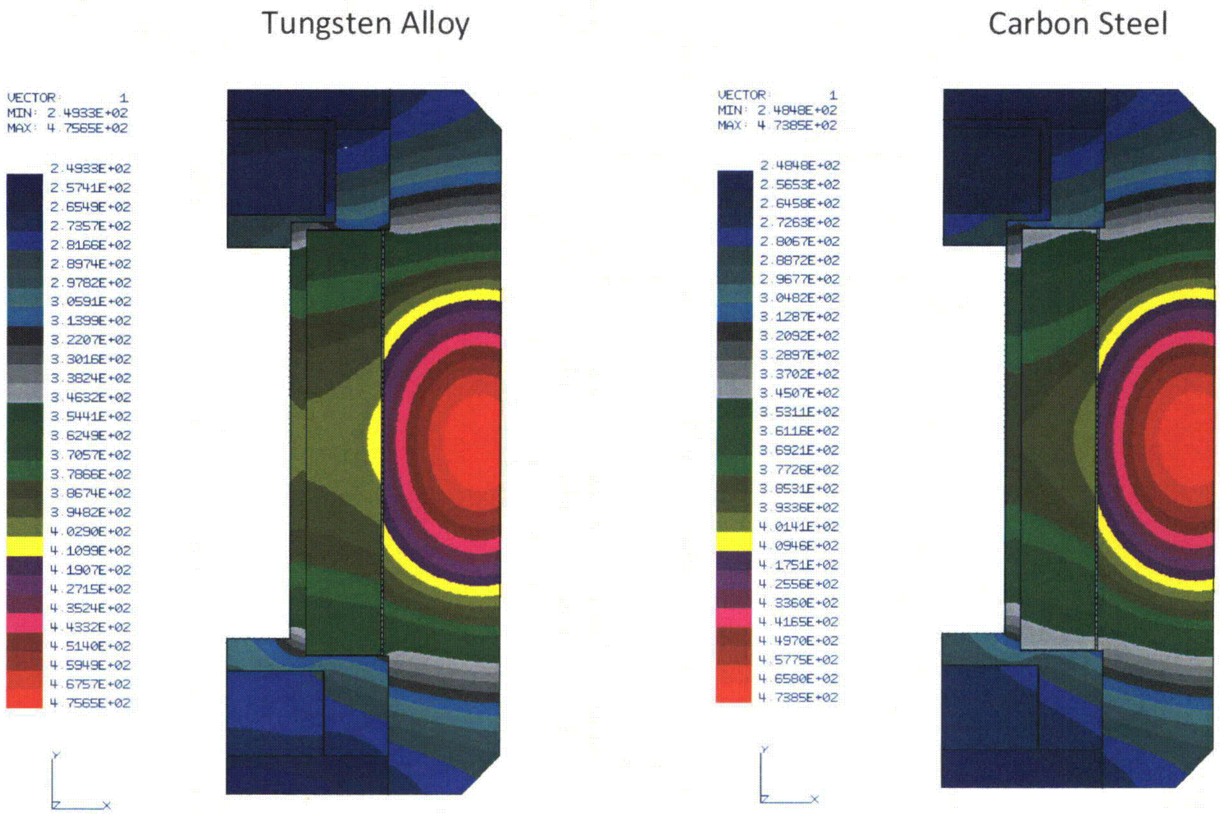

Figure 3-139. Load Case 112 – Fire at 60 Minutes, 100°F, 400W Decay Heat, Maximum Insolation, Cask Model – Tungsten Alloy (Model AOS-100A) and Carbon Steel (Model AOS-100B)

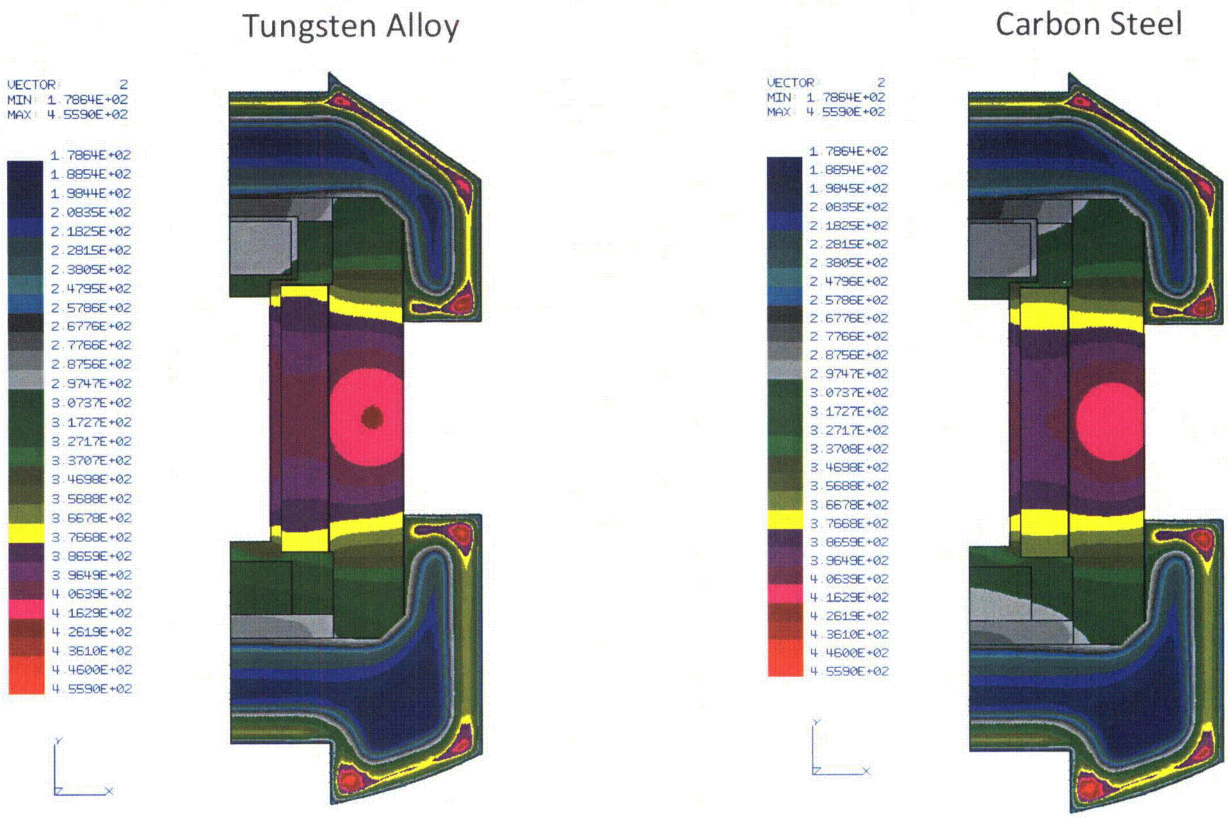

Figure 3-140. Load Case 113 – Fire at 90 Minutes, 100°F, 400W Decay Heat, Maximum Insolation, Entire Model – Tungsten Alloy (Model AOS-100A) and Carbon Steel (Model AOS-100B)

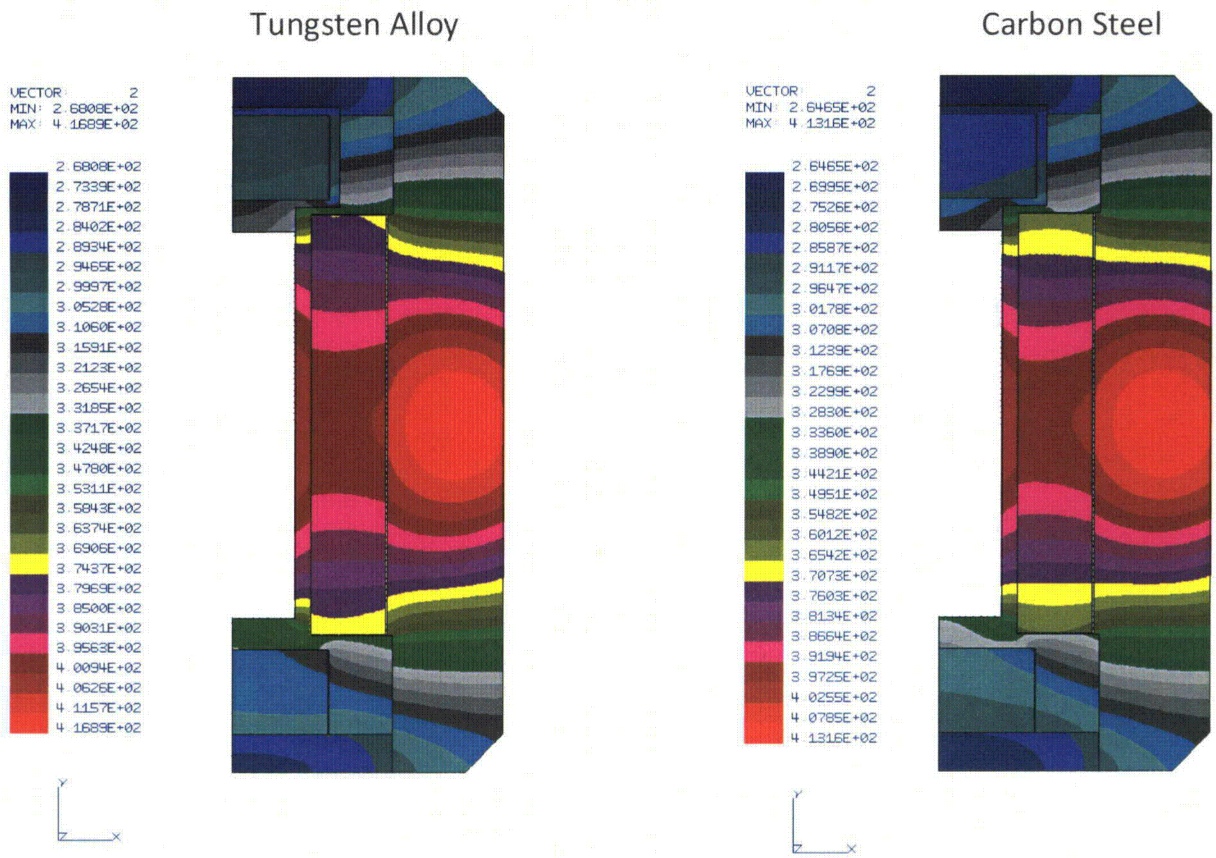

Figure 3-141. Load Case 113 – Fire at 90 Minutes, 100°F, 400W Decay Heat, Maximum Insolation, Cask Model – Tungsten Alloy (Model AOS-100A) and Carbon Steel (Model AOS-100B)

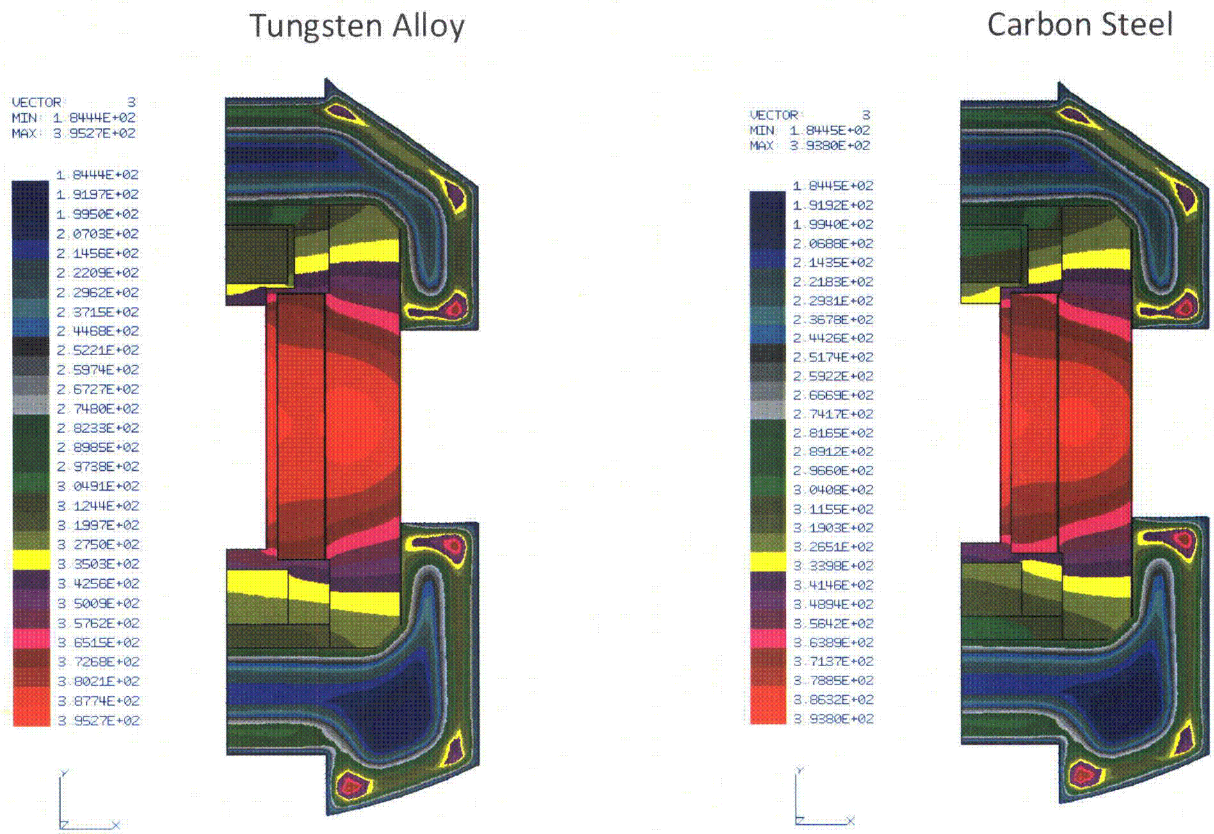

Figure 3-142. Load Case 114 – Fire at 120 Minutes, 100°F, 400W Decay Heat, Maximum Insolation, Entire Model – Tungsten Alloy (Model AOS-100A) and Carbon Steel (Model AOS-100B)

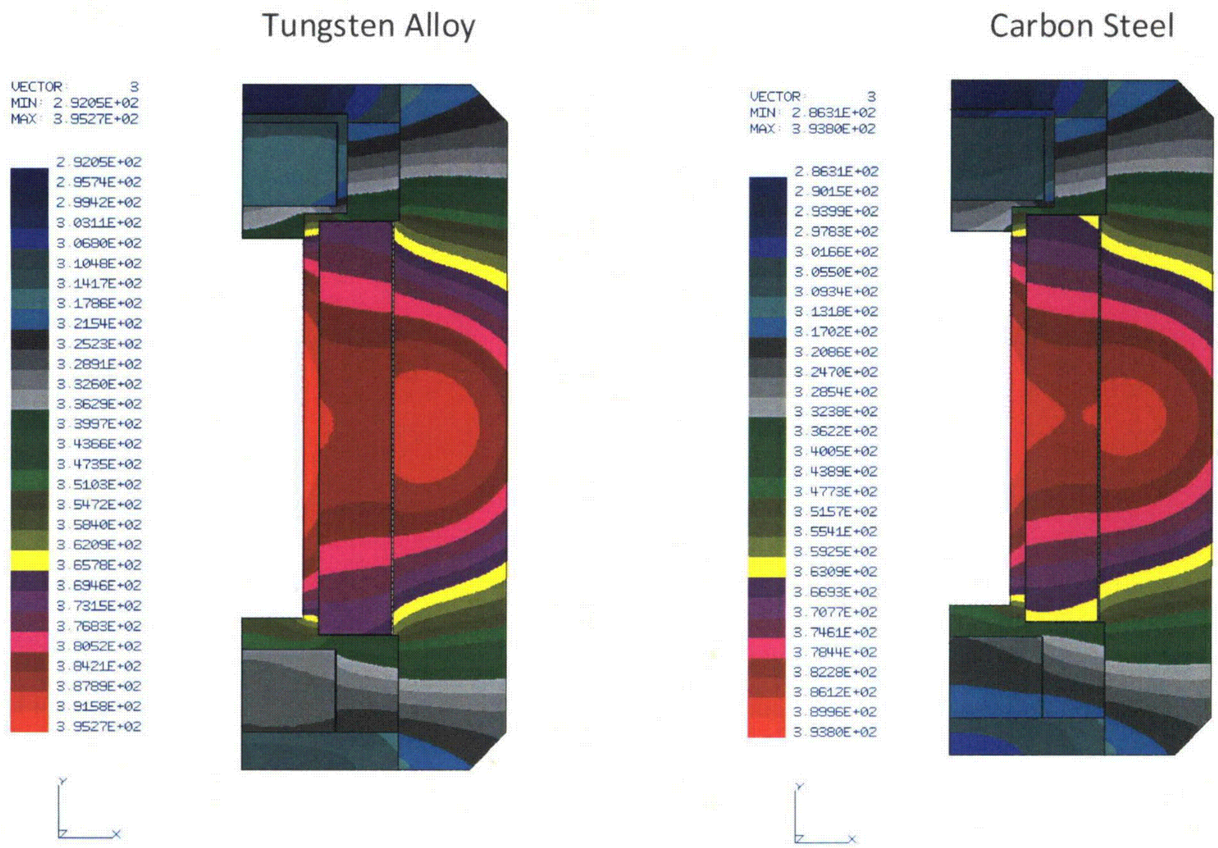

Figure 3-143. Load Case 114 – Fire at 120 Minutes, 100°F, 400W Decay Heat, Maximum Insolation, Cask Model – Tungsten Alloy (Model AOS-100A) and Carbon Steel (Model AOS-100B)

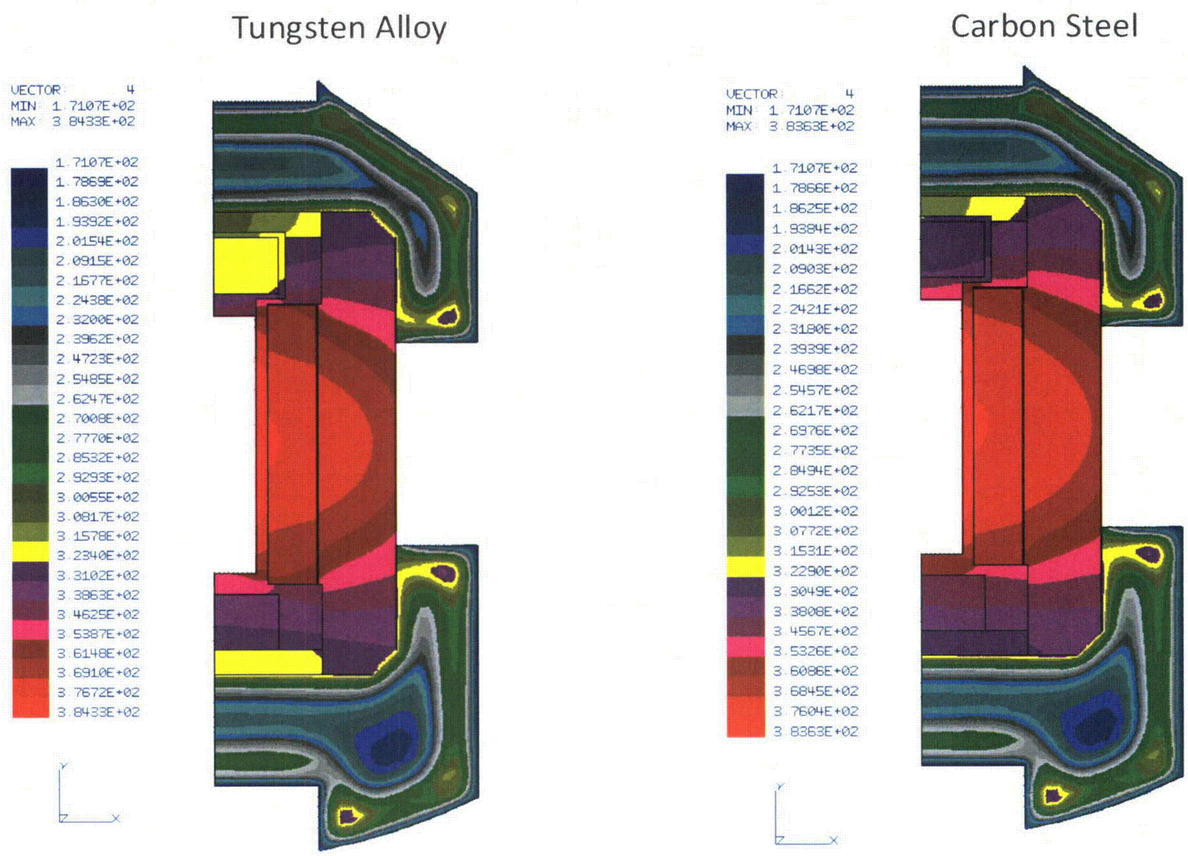

Figure 3-144. Load Case 115 – Fire at 150 Minutes, 100°F, 400W Decay Heat, Maximum Insolation, Entire Model – Tungsten Alloy (Model AOS-100A) and Carbon Steel (Model AOS-100B)

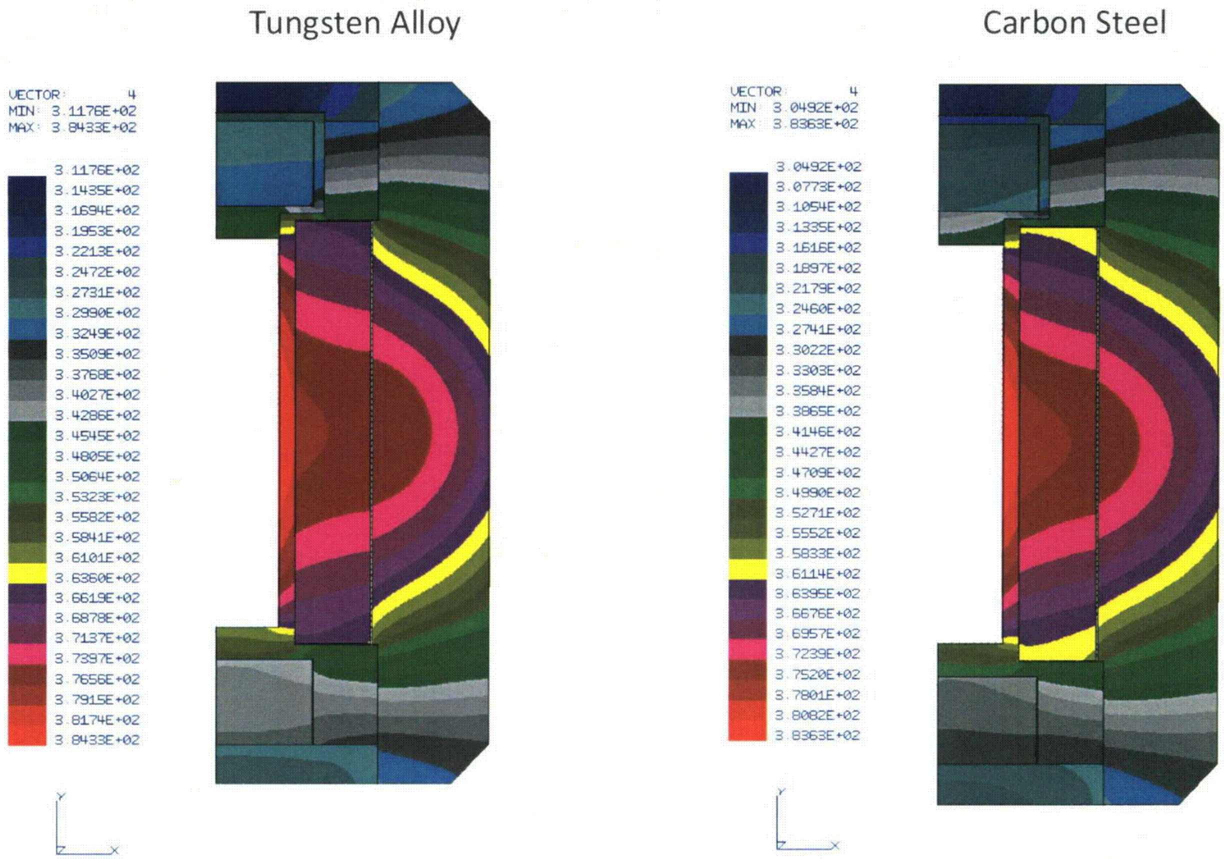

Figure 3-145. Load Case 115 – Fire at 150 Minutes, 100°F, 400W Decay Heat, Maximum Insolation, Cask Model – Tungsten Alloy (Model AOS-100A) and Carbon Steel (Model AOS-100B)

3.5.5 Material Properties Correlation between the Equations Provided in the Test and the LIBRA Input File

```
TI Load Case_111 - 100F Ambient, Max Decay Heat, max Insolation
*
mc 12 31 32 33 34
cnd  1      0.0,     0.0,      0.0
cnd  2      8.1185, 0.0,      0.0
cnd  3      13.688, 0.0,      0.0
cnd  103    13.70,  0.0,      0.0
cnd  4      18.10,  0.0,      0.0
cnd  104    18.10,  0.0,      0.0
cnd  5      19.88,  0.0,      0.0
cnd  6      0.0,    3.22,     0.0
cnd  106    0.0,    3.226,    0.0
cnd  7      4.6058, 3.226,    0.0
cnd  8      6.6528, 3.226,    0.0
cnd  9      8.188,  3.226,    0.0
cnd  109    8.25,   3.22,     0.0
cnd  1009   8.25,   3.226,    0.0
cnd  10     13.688, 3.22,     0.0
cnd  110    13.688, 3.226,    0.0
cnd  1010   13.70,  3.22,     0.0
cnd  11     18.10,  3.22,     0.0
cnd  111    18.10,  3.22,     0.0
cnd  12     19.6,   3.22,     0.0
cnd  13     23.1,   3.22,     0.0
cnd  14     0.0,    10.446,   0.0
cnd  114    0.0,    10.456,   0.0
cnd  15     5.36,   10.446,   0.0
cnd  115    5.36,   10.456,   0.0
cnd  16     6.725,   10.446,  0.0
cnd  116    6.725,   10.456,  0.0
cnd  17     8.188,  10.446,   0.0
cnd  117    8.25,   10.456,   0.0
cnd  18     13.1936,9.661,    0.0
cnd  19     13.688, 9.5815,   0.0
cnd  20     5.36,   12.024,   0.0
cnd  21     6.725,   11.70,    0.0
cnd  121    6.730,   11.763,  0.0
cnd  22     8.25,   11.70,    0.0
cnd  122    8.25,   11.763,   0.0
cnd  23     13.20,  11.70,    0.0
cnd  123    13.075, 11.763,   0.0
cnd  1023   13.20,  11.71,    0.0
cnd  24     13.688, 11.70,    0.0
cnd  124    13.70,  11.71,    0.0
cnd  25     18.10,  11.71,    0.0
cnd  125    18.10,  11.71,    0.0
cnd  26     23.10,  11.71,    0.0
cnd  27     0.0,    13.20,    0.0
cnd  28     5.36,   13.20,    0.0
cnd  29     6.725,   13.20,    0.0
```

```
cnd  129    6.730,   13.20,  0.0
cnd  30     8.25,   13.20,   0.0
cnd  31     13.075, 13.2262, 0.0
cnd  51     0.0,     46.20,  0.0
cnd  52     5.344,  46.20,   0.0
cnd  152    5.36,   46.20,   0.0
cnd  53     6.725,   46.20,   0.0
cnd  153    6.730,   46.20,  0.0
cnd  54     8.25,   46.20,   0.0
cnd  55     10.18, 46.20,   0.0
cnd  56     13.075,  46.20, 0.0
cnd  57     0.0,    47.70,   0.0
cnd  58     5.344,  47.70,   0.0
cnd  158    5.36,   47.70,   0.0
cnd  59     6.725,   47.70,   0.0
cnd  159    6.730,   47.637, 0.0
cnd  60     8.25,   47.637,  0.0
cnd  160    8.25,   47.70,   0.0
cnd  61     9.125,  47.637,  0.0
cnd  161    9.125,  47.70,   0.0
cnd  62     13.075, 47.637,  0.0
cnd  162    13.20,  47.69,   0.0
cnd  1062   13.20,  47.70,   0.0
cnd  63     13.688, 47.70,   0.0
cnd  163    13.70,  47.69,   0.0
cnd  64     18.10,  47.69,   0.0
cnd  164    18.10,  47.69,   0.0
cnd  65     23.10,  47.69,   0.0
cnd  66     0.0,    48.327,  0.0
cnd  67     5.344,  48.327,  0.0
cnd  167    5.36,   48.317,  0.0
cnd  68     6.725,   48.317,  0.0
cnd  168    6.725,   48.327,  0.0
cnd  69     8.25,   48.317,  0.0
cnd  169    8.25,   48.327,  0.0
cnd  70     9.125,  48.317,  0.0
cnd  170    9.075,  48.327,  0.0
cnd  71     13.0361,49.16566,0.0
cnd  72     13.688, 49.3071, 0.0
cnd  73     0.0,    48.944,  0.0
cnd  173    0.0,    48.954,  0.0
cnd  74     5.344,  48.944,  0.0
cnd  174    5.344,  48.954,  0.0
cnd  75     6.96914, 48.944, 0.0
cnd  76     8.188,  48.954,  0.0
cnd  176    8.25,   48.944,  0.0
cnd  78     9.075,  48.944,  0.0
cnd  178    9.125,  48.944,  0.0
cnd  79     13.688, 50.9243, 0.0
cnd  80     0.0,    56.174,  0.0
cnd  180    0.0,    56.18,   0.0
cnd  81     5.0417, 56.174,  0.0
cnd  82     8.188,  56.174,  0.0
cnd  182    8.25,   56.18,   0.0
```

```
cnd  83     9.075,  56.18,    0.0
cnd  183    9.125,  56.174,   0.0
cnd  1083   9.125,  56.18,    0.0
cnd  84     13.688, 56.174,   0.0
cnd  184    13.688, 56.18,    0.0
cnd  1084   13.70,  56.18,    0.0
cnd  85     18.10,  56.18,    0.0
cnd  185    18.10,  56.18,    0.0
cnd  86     19.60,  56.18,    0.0
cnd  87     23.1,   56.18,    0.0
cnd  88     0.0,    56.862,   0.0
cnd  188    0.0,    56.893,   0.0
cnd  89     8.25,   56.862,   0.0
cnd  189    8.25,   56.893,   0.0
cnd  90     9.075,  56.862,   0.0
cnd  190    9.125,  56.893,   0.0
cnd  92     13.688, 57.5657,  0.0
cnd  93     0.0,    59.40,    0.0
cnd  94     8.496,  59.40,    0.0
cnd  95     10.384, 59.40,    0.0
cnd  96     13.688, 59.40,    0.0
cnd  196    13.70,  59.40,    0.0
cnd  97     18.10,  59.40,    0.0
cnd  197    18.10,  59.40,    0.0
cnd  98     19.88,  59.40,    0.0
cnd  401    5.36,   42.2,     0.0
cnd  402    6.725,   42.2,     0.0
cnd  403    5.36,   43.2,     0.0
cnd  404    6.725,    43.2,     0.0
* impact limiter
cnd 201      0.0,     -.02,      0.0
cnd 202      0.0,     -14.19,    0.0
cnd 203      13.70,   -.02,      0.0
cnd 204     13.35,    -14.19,    0.0
cnd 205     13.35,    -22.39,    0.0
cnd 2050    14.101,   -22.251,   0.0
cnd 206      18.10,   -.02,      0.0
cnd 207     20.0442,  -7.4535,   0.0
cnd 208     24.808,   -19.366,   0.0
cnd 2080    21.856,   -20.333,   0.0
cnd 209      19.92,   -.02,      0.0
cnd 210     22.2703,  -5.2050,   0.0
cnd 211     28.66,    -17.896,   0.0
cnd 2110    31.125,   -16.825,   0.0
cnd 212     26.1625,  -3.0625,   0.0
cnd 213     33.55,    -15.66,    0.0
cnd 214     23.3,      3.18,     0.0
cnd 215     30.375,    .8180,    0.0
cnd 216     33.55,    -.38,      0.0
cnd 217     23.3,      11.71,    0.0
cnd 218     30.375,    11.71,    0.0
cnd 219     33.55,     11.71,    0.0
cnd 220     23.3,      16.71,    0.0
cnd 221     30.375,    16.71,    0.0
```

```
cnd 222     33.55,    16.71,   0.0
cnd 223     23.3,     42.69,   0.0
cnd 224     32.0,   42.69,   0.0
cnd 225     33.55,    42.69,   0.0
cnd 226     23.3,     47.69,   0.0
cnd 227     32.0,   47.69,   0.0
cnd 228     33.55,    47.69,   0.0
cnd 229     23.3,     56.22,   0.0
cnd 230     32.0,     60.5, 0.0
cnd 231     33.55,    61.83,   0.0
cnd 232     27.6,     63.7, 0.0
cnd 233     29.03,    65.04,   0.0
cnd 234     19.92,    59.42,   0.0
cnd 235     24.8,    66.1,   0.0
cnd 236     25.37,    67.65,   0.0
cnd 237     18.10,    59.42,   0.0
cnd 238     21.6,    68.6,   0.0
cnd 239     22.06,    70.00,   0.0
cnd 240     13.70,    59.42,   0.0
cnd 241     13.35,    73.59,   0.0
cnd 242     13.35,    76.19,   0.0
cnd 243     0.0,      59.42,   0.0
cnd 244     0.0,      73.59,   0.0
cnd 301     0.0,  -12.7,    0.0
cnd 302     13.35, -12.7,   0.0
cnd 303     14.85, -12.7,   0.0
cnd 304     14.85, -14.19,  0.0
cnd 305     13.35, -20.9,   0.0
cnd 306     14.85, -20.9,   0.0
cnd 307     14.85, -22.103,  0.0
cnd 308     27.9,  -16.3,   0.0
cnd 309     32.,  -14,   0.0
cnd 310     31.9,  0.2,     0.0
cnd 311     31.9,  11.71,   0.0
cnd 312     23.3,  15.21,   0.0
cnd 313     30.375, 15.21,   0.0
cnd 314     31.9,  15.21,   0.0
cnd 315     33.55, 15.21,   0.0
cnd 316     31.9,  16.71,   0.0
cnd 320     0.0,    72.1,  0.0
cnd 321     13.35,  72.1,  0.0
cnd 322     14.85,  74.8,  0.0
cnd 323     14.85,  73.5,  0.0
cnd 324     14.85,  72.1,  0.0
cnd 325     23.3,   44.2,  0.0
cnd 326     32.0,   44.2,  0.0
cnd 327     33.55,  44.2,  0.0
*                                        node/element range
*  part 1 Outer Stainless Steel shell     101 - 3000 - 101/1
*  part 2 Top+bottom plates              3001 - 4000 - 102/2
*  part 3 cavity Inner shell             4001 - 5000 - 103/3
*  part 4 Inner plug                     5001 - 6000 - 104/4
*  part 5 Tungsten cylinder              6001 - 8000 - 105/5
*  impact limiter foam                   8001 - 11000 - 106/6
```

```
* part 1 outer ss shell, prop/mat=101/1
G10
  10,8,   101,101,    34,101,,1   Identify the NM for the Element that creates.
  103,4,11,1010         See G10 record, attached.
-1
G10
  4,8,     -1,-1,     34,101,,1
  104,5,12,111
-1
G9
  8,8,8,  -1,-1,      31,34,101,,1
  5,13,12
-1
G10
  10,17,      -1,-1,  34,101,,1
  1010,11,25,124
-1
G10
  11,17,      -1,-1,  34,101,,1
  111,13,26,125
-1
G10
  2,73,   -1,-1,      34,101,,1
  1023,124,163,162
-1
G10
  10,73,  -1,-1,      34,101,,1
  124,25,64,163
-1
G10
  11,73,    -1,-1,    34,101,,1
  125,26,65,164
-1
G10
  10,22,  -1,-1,   34,101,,1
  163,64,85,1084
-1
G10
  11,22,  -1,-1,   34,101,,1
  164,65,87,185
-1
G10
  10,8,   -1,-1,   34,101,,1
  1084,85,97,196
-1
G10
  4,8,  -1,-1,     34,101,,1
  185,86,98,197
-1
G9
  8,8,8,    -1,-1,  31,34,101,,1
```

```
  87,98,86
-1
* part 2
* bottom cover plate, prop/mat 102/2
G10
  17,8,  3001,3001,    34,102,,1
  1,2,109,6
-1
G10
  12,8,  -1,-1,    34,102,,1
  2,3,10,109
-1
* lid cover plate
G10
  19,5,  -1,-1,    34,102,,1
  188,189,94,93
-1
G10
  5,5,  -1,-1,    34,102,,1
  189,190,95,94
-1
G10
  8,4,  -1,-1,    34,102,,1
  1083,184,92,190
-1
G10
  8,5,  -1,-1,    34,102,,1
  190,92,96,95
-1
* part 3 cavity inner shell, prop/mat 103/3
G10
   12,13,   4001,4001,   34,103,,1
   1009,110,19,117
-1
G10
   10,8,   -1,-1,     34,103,,1
   114,115,28,27
-1
G10
   5,5,   -1,-1,    34,103,,1
   115,116,21,20
-1
G10
   4,5,    -1,-1,    34,103,,1
   116,117,22,21
-1
G10
   11,5,   -1,-1,    34,103,,1
   117,18,23,22
-1
G10
```

```
   2,5,    -1,-1,      34,103,,1
   18,19,24,23
-1
G10
   5,4,    -1,-1,      34,103,,1
   20,21,29,28
-1
G10
   5,59,    -1,-1,      34,103,,1
   28,29,402,401
-1
G10
   5,3,    -1,-1,      34,103,,1
   401,402,404,403
-1
G10
   5,7,    -1,-1,      34,103,,1
   403,404,53,152
-1
G10
   5,4,    -1,-1,      34,103,,1
   152,53,59,158
-1
G10
   5,5,    -1,-1,    34,103,,1
   158,59,68,167
-1
G10
   4,5,    -1,-1,      34,103,,1
   59,160,69,68
-1
G10
   5,5,    -1,-1,      34,103,,1
   160,161,70,69
-1
G10
   7,5,    -1,-1,      34,103,,1
   161,1062,71,70
-1
G10
   2,5,    -1,-1,      34,103,,1
   1062,63,72,71
-1
G10
   8,5,    -1,-1,      34,103,,1
   70,72,79,178
-1
G10
   8,14,    -1,-1,    34,103,,1
   178,79,84,183
-1
```

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* part 4 - plug cylinder shell, prop/mat-104/4
*
G10
   12,4,    5001,5001,  34,104,,1
   51,52,58,57
-1
G10
   12,5,      -1,-1,    34,104,,1
   57,58,67,66
-1
G10
   12,5,     -1,-1,     34,104,,1
   66,67,74,73
-1
G10
   5,5,    -1,-1,       34,104,,1
   67,168,75,74
-1
G10
   4,5,      -1,-1,     34,104,,1
   168,169,176,75
-1
G10
   5,5,    -1,-1,       34,104,,1
   169,170,78,176
-1
G10
   5,14,      -1,-1,    34,104,,1
   176,78,83,182
-1
G10
   19,4,     -1,-1,     34,104,,1
   180,182,89,88
-1
G10
   5,4,    -1,-1,       34,104,,1
   182,83,90,89
-1
* part 5 Tungsten, prop/mat=105/5
* Tungsten at bottom
G10
   10,13,   6001,6001,  34,105,,1
   106,7,15,14
-1
G10
   5,13,   -1,-1,       34,105,,1
   7,8,16,15
-1
G10
   4,13,   -1,-1,       34,105,,1
   8,9,17,16
```

```
-1
* side tungsten
G10
  4,4,   -1,-1,         34,105,,1
  121,122,30,129
-1
G10
  11,4,   -1,-1,        34,105,,1
  122,123,31,30
-1
G10
  4,67,   -1,-1,        34,105,,1
  129,30,54,153
-1
G10
  11,67,   -1,-1,       34,105,,1
  30,31,56,54
-1
G10
  4,4,   -1,-1,         34,105,,1
  153,54,60,159
-1
G10
  5,4,   -1,-1,         34,105,,1
  54,55,61,60
-1
G10
  7,4,   -1,-1,         34,105,,1
  55,56,62,61
-1
*  Tungsten in plug
G10
  12,14,  -1,-1,    34,105,,1
  173,174,81,80
-1
G10
  8,14,  -1,-1,    34,105,,1
  174,76,82,81
-1
*
* impact limiter
* bottom section
G10
   28,8,  8001,8001,     34,106,,1
   301,302,203,201
-1
G10
   28,16,  -1,-1,     34,106,,1
   202,204,302,301
-1
G10
```

```
   16,16,     -1,-1,       34,106,,1
   205,307,306,305
   5,2050
-1
G10
   16,6,     -1,-1,       34,106,,1
   305,306,304,204
-1
G10
   16,16,     -1,-1,       34,106,,1
   204,304,303,302
-1
g8
    16,8,10,8   -1,-1,   31,34,106,,1
   302,303,206,203
-1
G8
   11,7,11,16  -1,-1,     31,34,106,,1
   304,308,210,303
-1
G9
   8,8,8       -1,-1,     31,34,106,,1
   206,303,207
-1
G10
   4,8         -1,-1,     34,106,,1
   207,210,209,206
-1
G9
   6,11,11       -1,-1,     31,34,106,,1
   304,306,308
-1
G10
   11,16         -1,-1,     34,106,,1
   307,211,308,306
   5,2080
-1
G9
   8,8,8       -1,-1,     31,34,106,,1
   214,209,212
-1
G9
   8,8,8       -1,-1,     31,34,106,,1
   209,210,212
-1
G9
   8,8,8       -1,-1,     31,34,106,,1
   212,215,214
-1
G10
   8,16,       -1,-1,      34,106,,1
```

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   211,213,309,308
   5,2110
-1
G10
   8,7,       -1,-1,        34,106,,1
   308,309,212,210
-1
G10
   8,16,     -1,-1,         34,106,,1
   213,216,310,309
-1
G10
   8,7,       -1,-1,     34,106,,1
   309,310,215,212
-1
G10
   17,16     -1,-1,         34,106,,1
   216,219,311,310
-1
G10
   17,7     -1,-1,         34,106,,1
   310,311,218,215
-1
G10
   17,8     -1,-1,         34,106,,1
   215,218,217,214
-1
G10
   8,16     -1,-1,         34,106,,1
   219,315,314,311
-1
G10
   8,7     -1,-1,         34,106,,1
   311,314,313,218
-1
G10
   8,8     -1,-1,         34,106,,1
   218,313,312,217
-1
G10
   16,16     -1,-1,         34,106,,1
   315,222,316,314
-1
G10
   16,7     -1,-1,         34,106,,1
   314,316,221,313
-1
G10
   16,8     -1,-1,         34,106,,1
   313,221,220,312
-1
```

```
* top section
G10
   30,16,  15001,15001,      34,1060,,1
   320,321,241,244
-1
G10
   30,8,  -1,-1,      34,1060,,1
   243,240,321,320
-1
G10
   16,16,    -1,-1,        34,1060,,1
   241,323,322,242
-1
G10
   16,16,    -1,-1,        34,1060,,1
   321,324,323,241
-1
G8
   10,8,16,8    -1,-1,       31,34,1060,,1
   240,237,324,321
-1
G10
   8,16,    -1,-1,        34,1060,,1
   323,238,239,322
-1
G9
   8,8,8,    -1,-1,       31,34,1060,,1
   237,238,324
-1
G9
  8,8,16,    -1,-1,      31,34,1060,,1
  324,238,323
-1
G10
   4,16          -1,-1,              34,1060,,1
   238,235,236,239
-1
G10
   4,8          -1,-1,              34,1060,,1
   237,234,235,238
-1
G9
   8,8,8        -1,-1,              31,34,1060,,1
   234,229,232
-1
G9
   8,8,8        -1,-1,              31,34,1060,,1
   235,234,232
-1
G9
   8,8,8        -1,-1,              31,34,1060,,1
```

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   229,230,232
-1
G10
   8,16,      -1,-1,                 34,1060,,1
   235,232,233,236
-1
G10
   8,16     -1,-1,                   34,1060,,1
   232,230,231,233
-1
G10
   22,16    -1,-1,                    34,1060,,1
   228,231,230,227
-1
G10
   22,8    -1,-1,                    34,1060,,1
   227,230,229,226
-1
G10
   8,16    -1,-1,                    34,1060,,1
   327,228,227,326
-1
G10
   8,8    -1,-1,                    34,1060,,1
   326,227,226,325
-1
G10
   16,16    -1,-1,                    34,1060,,1
   225,327,326,224
-1
G10
   16,8    -1,-1,                    34,1060,,1
   224,326,325,223
-1
*
scale   0.606061,,101,18126
*  interface surface 1D elements, type 33
*  el,#,type,prop,n1,n2,total,incr1,incr2
*  tungsten gaps pr=151 pressure contact,152=steel wool
*  bottom 0.0 gaps
el   20001,33,151,   3120,6001,   10,1,1
el   20011,33,151,   3130,6132,   4,1,1
el   20015,33,151,   3134,6197,   3,1,1
el   20018,33,151,   6121,4157,   10,1,1
el   20028,33,151,   6192,4238,   4,1,1
el   20032,33,151,   6245,4263,   2,1,1
el   20034,33,151,   6247,4145
* gap steel wool
el   20035,33,152,   6199,4001,   13,4,12
* side tungsten - 0.003" gaps
el   20048,33,153,   4261,6248
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el   20049,33,153,    4356,6252,   3,5,4
el   20052,33,153,    4376,6312,   58,5,4
el   20110,33,153,    4671,6544,   2,5,4
el   20112,33,153,    4686,6552,   6,5,4
el   20118,33,153,    4721,7317,   3,5,4
* .07576" gap - steel wool
el   20121,33,156,    6274,606,    4,11,2
el   20125,33,156,    6597,614,    66,11,2
el   20191,33,156,    7362,746,    3,7,2
* .03788" gap - steel wool, top and bottom
el   20194,33,154,    4261,6248
el   20195,33,154,    4279,6249,   3,1,1
el   20198,33,154,    4327,6265,   10,1,1
el   20208,33,154,    7325,4731
el   20209,33,154,    7326,4758,   3,1,1
el   20212,33,154,    7345,4778,   4,1,1
el   20216,33,154,    7371,4803,   6,1,1
* top tungsten - 0.0 gap
el   20222,33,155,    5157,7377,   12,1,1
el   20234,33,155,    5190,7546,   4,1,1
el   20238,33,155,    5211,7550,   3,1,1
el   20241,33,155,    7533,5309,   12,1,1
el   20253,33,155,    7650,5321,   6,1,1
el   20259,33,155,    7656,5304
* gap steel wool
el   20260,33,157     7552,5213
el   20261,33,157,    7560,5244,   13,8,5
* contact-outer shell and bottom plate, low press cont.
***weld at el 20401
el   20401,33,109,    3148,101
el   20402,33,161,    3160,111    7,12,10
* contact-bottom cavity shell and outer shell, low press cont.
***weld at el 20409
el   20409,33,1090,    4012,171
el   20410,33,161,    4024,259,    12,12,10
el   20422,33,161,    4340,379,    4,2,10
el   20426,33,160,    4346,409                ;.303" lip
el   20427,33,160,    4336,606                ;.303" lip
* contact-bottom cavity shell and bottom plate, low press cont.
el   20428,33,162,    3136,4001
el   20429,33,162,    3222,4002,   11,1,1
* contact-lid and outer shell at top .007"
el   20440,33,163,    3360,2495
el   20441,33,163,    3368,2757,   3,8,10
el   20444,33,163,    3400,2787,   4,8,10
*
el   20448,33,160,    750,4808,    2,1,30   ;.303" lip
* contact-cavity and outer shells gap=.007"
el   20450,33,163,    4838,751
el   20451,33,163,    4840,2295,   4,2,10
el   20455,33,163,    4862,2335,   4,8,10
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el   20459,33,163,    4902,2375,    12,8,10
***weld at el 20471
el   20471,33,1090,   4998,2495
* contact lid and cavity top 0.0 gap
el   20472,33,164,    4991,3353,    8,1,1
* contact cavity wall and plug - lower vertical I/F .010"
el   20480,33,165,    5012,4707
el   20481,33,165,    5024,4717,    3,12,5
el   20484,33,165,    5072,4737,    4,12,5
* contact cavity wall and plug - horizontal plane 0.0 gap
el   20488,33,166,    4752,5169,    5,1,1
el   20493,33,166,    4774,5195,    3,1,1
el   20496,33,166,    4798,5215,    4,1,1
* contact cavity wall and plug - upper vertical I/F .030"
el   20500,33,167     5218,4801
el   20501,33,167,    5223,4855,    4,5,8
el   20505,33,167,    5248,4895,    13,5,8
* contact lid and plug - .019"@top,.0303"@side
el   20518,33,167,    5308,3353
el   20519,33,167,    5394,3361,    2,5,8
el   20521,33,167,    5404,3332
el   20522,33,168,    5366,3233,    19,1,1
el   20541,33,168,    5401,3329,    4,1,1
* gap between cask and impact limiter
* lower segment 0.0 gp
el   20825,33,170,    3001,8197,   17,1,1
el   20842,33,170,    3138,8214,   11,1,1
el   20853,33,170,    101,8224
el   20854,33,170,    102,9289
el   20855,33,170,    103,9288
el   20856,33,170,    104,9287
el   20857,33,170,    105,9286
el   20858,33,170,    106,9285
el   20859,33,170,    107,9284
el   20860,33,170,    108,9283
el   20861,33,170,    109,9282
el   20862,33,170,    110,9281
el   20863,33,170,    181,9281
el   20864,33,170,    182,9569,    3,1,1
* pr171=0.121" air gap
el   20867,33,171,    215,9812
el   20868,33,171,    218,9805
el   20869,33,171,    222,9799
el   20870,33,171,    227,9794
el   20871,33,171,    233,9790
el   20872,33,171,    240,9787
el   20873,33,171,    248,9785
el   20874,33,171,    440,10772,    16,11,1
el   20890,33,171,    1503,11029,   7,11,1
el   20897,33,171,    1580,11521,   3,11,5
* upper segment
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el   20900,33,171,   2174,18111, 4,11,5
el   20904,33,171,   2218,17736, 6,11,1
el   20910,33,171,   2284,17742
el   20911,33,171,   2526,17530,  20,11,1
el   20931,33,171,   2746,16694
el   20932,33,171,   2861,16686
el   20933,33,171,   2864,16679
el   20934,33,171,   2868,16673
el   20935,33,171,   2873,16668
el   20936,33,171,   2879,16664
el   20937,33,171,   2886,16661
* 0.0 gap
el   20938,33,170,   3309,15481,   19,1,1
el   20957,33,170,   3349,15500,   4,1,1
el   20961,33,170,   3418,15504,   7,1,1
el   20968,33,170,   2817,15510
el   20969,33,170,   2818,16234,   9,1,1
el   20978,33,170,   2855,16242
el   20979,33,170,   2856,16628,   3,1,1
* 304SS impact limiter shell
* bottom
el   21001,33,107,   8225,8226,27,1,1
el   21028,33,107,   8929,8945,5,16,16
el   21033,33,107,   8673,8689,15,16,16
el   21048,33,107,   8673,8674,15,1,1
el   21063,33,107,   9609,9610,10,1,1
el   21073,33,107,   9893,9894,7,1,1
el   21080,33,107,   10077,10078,7,1,1
el   21087,33,107,   10261,10262,16,1,1
el   21103,33,107,   10788,10789,7,1,1
el   21110,33,107,   11036,11037,15,1,1
el   21125,33,107,   11051,11067,15,16,16
el   21140,33,107,   11307,11323,6,16,16
el   21146,33,107,   11419,11435,7,16,16
el   21153,33,108,   8197,8198,27,1,1
el   21180,33,108,   9281,9282,9,1,1
el   21189,33,107,   9568,9569,3,1,1
el   21190,33,107,   9820,9812
el   21191,33,107,   9812,9805
el   21192,33,107,   9805,9799
el   21193,33,107,   9799,9794
el   21194,33,107,   9794,9790
el   21195,33,107,   9790,9787
el   21196,33,107,   9787,9785
el   21197,33,107,   10771,10772,16,1,1
el   21213,33,107,   11028,11029,7,1,1
el   21220,33,107,   11516,11517,15,1,1
* top
el   21301,33,107,   15451,15452,29,1,1
el   21330,33,107,   15721,15737,15,16,16
el   21345,33,107,   15961,15962,15,1,1
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el   21360,33,107,    16454,16455,7,1,1
el   21367,33,107,    16623,16624,3,1,1
el   21370,33,107,    16887,16888,7,1,1
el   21377,33,107,    17015,17016,7,1,1
el   21384,33,107,    17023,17024,21,1,1
el   21405,33,107,    17551,17552,7,1,1
el   21412,33,107,    17743,17744,15,1,1
el   21427,33,107,    17743,17759,15,16,16
el   21443,33,107,    17999,18015,7,16,16
el   21450,33,107,    18111,18112,15,1,1
el   21565,33,107,    17735,17736,7,1,1
el   21572,33,107,    17529,17530,21,1,1
el   21573,33,107,    16630,16661
el   21574,33,107,    16661,16664
el   21575,33,107,    16664,16668
el   21576,33,107,    16668,16673
el   21577,33,107,    16673,16679
el   21578,33,107,    16679,16686
el   21579,33,107,    16686,16694
el   21580,33,108,    15481,15482,29,1,1
el   21609,33,108,    16233,16234,9,1,1
el   21618,33,108,    16627,16628,3,1,1
*
*  outer surface convective elements - 32's
* surface 1
el   22001,32,110,    8225,8226,27,1,1
* surface 2
el   22028,32,111,    8929,8945,5,16,16
el   22033,32,111,    8673,8689,15,16,16
* surface 3
el   22048,32,112,    8673,8674,15,1,1
el   22063,32,112,    9609,9610,10,1,1
el   22073,32,112,    9893,9894,7,1,1
* surface 4
el   22080,32,113,    10077,10078,7,1,1
el   22087,32,113,    10261,10262,16,1,1
el   22106,32,113,    10788,10789,7,1,1
el   22113,32,113,    11036,11037,15,1,1
* surface 5
el   22128,32,114,    11051,11067,15,16,16
el   22143,32,114,    11307,11323,6,16,16
el   22149,32,114,    11419,11435,7,16,16
* surface 6 side
el   22156,32,115,    1602,1613,52,11,11
* surface 7
el   22208,32,116,    17743,17759,15,16,16
el   22223,32,116,    17999,18015,7,16,16
* surface 8
el   22230,32,117,    17743,17744,15,1,1
el   22245,32,117,    17551,17552,7,1,1
el   22252,32,117,    17023,17024,21,1,1
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* surface 9
el   22273,32,118,   15961,15962,15,1,1
el   22288,32,118,   16454,16455,7,1,1
el   22295,32,118,   16623,16624,3,1,1
el   22298,32,118,   16887,16888,7,1,1
el   22305,32,118,   17015,17016,7,1,1
* surface 10
el   22312,32,119,   15721,15737,15,16,16
* surface 11
el   22327,32,120,   15451,15452,29,1,1
* cavity decay heat boundary elements
el   23001,32,121,   4227,4228,9,1,1
el   23010,32,121,   4236,4372
el   23011,32,121,   4372,4377,57,5,5
el   23069,32,121,   4657,4667
el   23070,32,121,   4667,4672
el   23071,32,121,   4672,4682
el   23072,32,121,   4682,4687,5,5,5
el   23077,32,121,   5001,5002,11,1,1
me 0.001
* Element Properties - axisymmetric
* stif34 - pr,pr#,mat#,thk,q,h,t(bath)
pr  101,1,0.0,0.0,0.0,0.0          ; 304ss outer shell.  NM 101, thermal
                                                        Properties located in 1.
                                                        See PR record, attached.
pr  102,2,0.0,0.0,0.0,0.0          ; 304ss bottom plate and lid
pr  103,3,0.0,0.0,0.0,0.0          ; 304ss cavity shell
pr  104,4,0.0,0.0,0.0,0.0          ; 304ss plug shell
pr  105,5,0.0,0.0,0.0,0.0          ; tungsten
pr  106,6,0.0,0.0,0.0,0.0          ; foam-15 pcf lower IL
pr  1060,66,0.0,0.0,0.0,0.0        ; foam-21 pcf upper IL
*  stif33 input - pr,pr#pr,mat#,area,q,conv flag, h
pr  107,7,.105,0.0,0,0,            ; impact limiter 12 gage shell
pr  108,7,.188,0.0,0,0,            ; impact limiter .188" base plate
pr  109,8,.625, 0.0,0,0,           ; 5/8" weld
pr  1090,8,.50,0.0,0,0,            ; 1/2" weld
pr  1,-201,-202,.29              ; 304ss  PR record for 1, points to Properties
                                   records, 201 and 202. Minus (-) in
                                   front identified that the properties
                                   are a function of Temperature.
pr  2,-201,-202,.29               ; 304ss
pr  3,-201,-202,.29               ; 304ss
pr  4,-201,-202,.29               ; 304ss
pr  5,-203,-204,.654              ; tungsten
pr  6,.00227,.353,.0087           ; foam - 15 lb/ft3
pr  66,.00261,.353,.0122           ; foam - 21 lb/ft3
pr  7,-201,-202,.29               ; a304 ss overpack shell
pr  8,-201,-202,.29               ; a304 weld material
*  stif33 input - elpr,matpr,area,heat flux,conv flag, h
pr  151,11,0.32,   0.0,1,0.231     ; 0.0 y gap tungsten-304 I/F
pr  152,12,0.36,   0.0,,           ; .038" x gap with stl wool tungsten I/F
```

```
pr  153,18,0.30,   0.0,,           ; 0.003" x gap tungsten I/F
pr  154,11,0.31,   0.0,1,0.231  ; 0.0 y gap, shimmed,  I/F
pr  155,11,0.29,   0.0,1,0.231  ; 0.0 y gap tungsten-304 I/F
pr  156,12,0.30,   0.0,,        ; .76" x gap with stl wool tungsten I/F
pr  157,12,0.34,   0.0,,        ; top tungsten w/ stl wool
pr  160,11,.15,    0.0,1,0.231  ; .30" lip cavity to outer shells
pr  161,11,0.31,   0.0,1,0.231  ; 0.0 x gap 304 to 304 I/F's
pr  162,11,0.30,   0.0,1,0.231  ; 0.0 y gap 304 to 304 I/F's
pr  163,13,0.25,   0.0,,        ; 0.007" x gap lid+cavity-outer
pr  164,11,0.39,  0.0,1,0.231   ; 0.0 y gap lid to cavity surface @ bolt
pr  165,14,0.18,  0.0,,          ; 0.010" x-gap plug-cavity wall lower vertical
pr  166,11,0.21,  0.0,1,0.231   ; 0.0 y gap horz plane cavity-plug
pr  167,15,0.26,  0.0,,          ; 0.030" x gap plug-cavity wall upper vertical
pr  168,16,0.25,  0.0,,         ; 0.019" y gap conv+rad  plug-lid
pr  170,11,0.31,  0.0,1,0.231   ; 0.0 y gap cask-over pack i/f
pr  171,17,0.32,  0.0,,         ; cask-over pack 0.121" x gap
* Thermal material properties - prop#,kx,c,m,e,ky,kz
pr  11,0.0,0.0,0.0,,,           ; convect.i/p see pr
151,161,162,164,166,169,170
pr  12,.068,.24,.029             ; stl wool -
k=.1*k(304),c=c(air),den=.1*d(304)
pr  13,-216,-220,-221            ; enclosed air pr 163 s=.012"
pr  14,-217,-220,-221            ; enclosed air pr 165 s=.016"
pr  15,-218,-220,-221            ; enclosed air pr 153,and 167 s=.050"
pr  16,-219,-220,-221            ; enclosed air pr 168 s=.031"
pr  17,-222,-220,-221            ; air gap 0.2" at over pack i/f
pr  18,-223,-220,-221            ; air gap 0.005" at side tungsten i/f
```

pr 201, .6851, 4.544e-4,-4.126e-8 ; poly.coef.304ss cond. ***Polynomial***
pr 202, .1120, 3.504e-5,-1.080e-8 ; poly.coef.304ss.sp.ht. ***Coefficients.***

REFER TO THE CONDUCTIVITY AND SPECIFIC HEAT EQUATIONS PROVIDED IN CHAPTER 3, Paragraph 3.2.1.1, FOR A COMPARISON OF THE COEFFICIENTS SHOWN ABOVE, AND THOSE PRESENTED IN THE EQUATIONS.

```
pr  203,  3.673,     4.028e-4,-4.167e-7     ; tung.cond-test data
pr  204,  3.631e-2, 8.017e-6,-1.807e-9     ; tung.sp.ht.-test data
pr  205,  9.326e-3, 6,712e-6, 2.299e-8     ; h surf.1, e=.52
pr  206,  9.326e-3, 6,712e-6, 2.299e-8     ; h surf.2, e=.52
pr  207,  9.326e-3, 6,712e-6, 2.299e-8     ; h surf.3, e=.52
pr  208,  1.094e-2, 9.294e-6, 2.185e-8     ; h surf.4, e=.52
pr  209,  9.326e-3, 6,712e-6, 2.299e-8     ; h surf.5, e=.52
pr  210,  8.395e-3, 9.959e-6, 5.634e-9     ; h surf.6, e=.20
pr  211,  9.326e-3, 6,712e-6, 2.299e-8     ; h surf.7, e=.52
pr  212,  1.094e-2, 9.294e-6, 2.185e-8     ; h surf.8, e=.52
pr  213,  9.326e-3, 6,712e-6, 2.299e-8     ; h surf.9, e=.52
pr  214,  9.916e-3, 7.736e-6, 2.252e-8     ; h surf.10, e=.52
pr  215,  9.326e-3, 6,712e-6, 2.299e-8     ; h surf.11, e=.52
pr  216,  1.130e-3,  2.041e-6, -3.541e-13  ; k enclosed air pr 163-.007"
pr  217,  1.138e-3,  2.022e-6,  1.691e-10  ; k enclosed air pr 165-.010"
pr  218,  1.196e-3,  1.900e-6,  1.298e-9   ; k enclosed air pr 167-.030"
pr  219,  1.164e-3,  1.967e-6,  6.773e-10  ; k enclosed air pr 168-.019"
```

```
pr  220,  2.402e-1, -1.401e-6,  3.995e-8,-1.570e-11  ; Cp enclosed air
pr  221,  4.684e-5, -7.150e-8,  5.869e-11,-1.834e-14 ; density enclosed air
pr  222,  1.458e-3,  1.346e-6,  6.437e-9   ; k enclosed air overpack pr171-
.121"
pr  223,  1.118e-3,  2.065e-6, -2.262e-10  ; k enclosed air tungsten pr153-
.003"
*  32's pr,pr#,h,thk,Temp,q,e
*  solar heat
pr  110,-205,     0.0,100,  0.4267,0.0  ; conv. surf.1 - 200c/cm2
pr  111,-206,     0.0,100,  0.8533,0.0  ; conv. surf.2 - 400c/cm2
pr  112,-207,     0.0,100,  0.8533,0.0  ; conv. surf.3 - 400c/cm2
pr  113,-208,     0.0,100,  0.8533,0.0  ; conv. surf.4 - 400c/cm2
pr  114,-209,     0.0,100,  0.4267,0.0  ; conv. surf.5 - 200c/cm2
pr  115,-210,     0.0,100,  0.8533,0.0  ; conv. surf.6 - 400c/cm2
pr  116,-211,     0.0,100,  0.4267,0.0  ; conv. surf.7 - 200c/cm2
pr  117,-212,     0.0,100,  0.8533,0.0  ; conv. surf.8 - 400c/cm2
pr  118,-213,     0.0,100,  0.8533,0.0  ; conv. surf.9 - 400c/cm2
pr  119,-214,     0.0,100,  0.8533,0.0  ; conv. surf.10- 400c/cm2
pr  120,-215,     0.0,100,  0.4267,0.0  ; conv. surf.11- 200c/cm2
pr  121,0.0,      0.0,70,   2.875     ; decay heat - 400 W
sc   20,1,1,10,0,     1,0,0.1,1.0,70, 1.0,1,,        ; SS with decay heat
end
```

Generate 2D Region by Isoparametric Mapping (G10)

G10 generates regions of 3- or 4-node elements and nodes by mapping with quadratic, isoparametric functions. Both flat and curved surfaces can be generated, with curved surfaces and curved boundaries mapped by parabolic functions. Mesh density is controlled by the location of mid-side nodes. By placing the mid-side node closer to a corner, the mesh density is increased in the corner region. This generator is flagged by a record containing only the descriptor G10 .

The coordinates of the control points (corners and mid-sides of the generated region) may entered directly, or by defining them on CND records and specifying the CND node ID numbers.

Control Data Record for Generator 10

ITEM	DESCRIPTION	SYMBOL
1	Number of nodes along side 1	N1
2	Number of nodes along side 2	N2
3	Number of first node (1)	NND1
4	Number of first element (2)	NEL1
5	Element type (3)	NET
6	Associated property set	MAT
7	Flag for local coordinates (4)	LCS
8	Flag for control points (5)	ICTLPT

Notes

1) If NND1=-1, node numbering continued from highest node number. The highest node and element numbers are listed on file MAX_NODE.
2) If NEL1=-1, element numbering continued from the highest element number. If NEL1=0, no elements are generated.
3) If NET, MAT, LCS and ICTLPT are omitted, values from last call to G10 used.
4) If control nodes are entered in local coordinates, set LCS=1
5) If the corners and mid-sides of the generated region are defined on Control Point Records, set ICTLPT=1 . Otherwise set ICLTPT=0 .

First Corner Node Data Record

If ICLTPT=0:

ITEM	DESCRIPTION	SYMBOL
1	X-coordinate of first node	X1
2	Y-coordinate of first node	Y1
3	Z-coordinate of first node	Z1
4	X-coordinate of second node	X2
5	Y-coordinate of second node	Y2
6	Z-coordinate of second node	Z2

If ICLTPT=1:

ITEM	DESCRIPTION	SYMBOL
1	ID number of first corner point	NCP(1)
2	ID number of second corner point	NCP(2)
3	ID number of third corner point	NCP(3)
4	ID number of forth corner point	NCP(4)

Second Corner Node Data Record

This record is omitted if the corners and mid-sides of the generated region are specified by defining the points with ID numbers.

ITEM	DESCRIPTION	SYMBOL
1	X-coordinate of third node	X3
2	Y-coordinate of third node	Y3
3	Z-coordinate of third node	Z3
4	X-coordinate of forth node	X4
5	Y-coordinate of forth node	Y4
6	Z-coordinate of forth node	Z4

Mid-Side Node Data Record

This data record defines a mid-side node, and is required for each mid-side node. Mid-side nodes are only required for curved boundaries.

If ICLTPT=0:

ITEM	DESCRIPTION	SYMBOL
1	Number of mid side node (1)	NND
2	X-coordinate of mid-side node	X
3	Y-coordinate of mid-side node	Y
4	Z-coordinate of mid-side node	Z

If ICLTPT=1:

ITEM	DESCRIPTION	SYMBOL
1	Number of mid side node (1)	NND
2	ID number of mid-side point	NCP

Notes

1) The four corner nodes are numbered 1-4. The mid-side nodes are numbered 5-8 as follows:

Corner Node Nos.	Mid-Side Node No.
1,2	5
2,3	6
3,4	7
4,1	8

Termination Record for Mid-Side Nodes

This data record terminates mid-side data. The record contains only -1, and is required even if no mid-side nodes are entered.

ITEM	DESCRIPTION	SYMBOL
	-1	

Element Property Set Record (PR)

All element data is entered on Element Property records. This section defines the format of Element Property records, the specific data entries are defined in the Element Property Manual for the various element types.

The connection between elements and property records is the element property number. This number is entered on the element definition record (or specified to the model generator) and defines the first property record required by the element.

ITEM	DESCRIPTION	SYMBOL
	Descriptor (PR)	
1	Property set number (1)	NM
2	First field of property set	PR_1
3	Second field of property set	PR_2
...	...	...
8	Eighth field of property set	PR_8

Notes:

1) Maximum value, NM=99999

Thermal Material Properties (THE_PROP)

This record defines constant thermal properties, or pointers to temperature-dependent property sets. For temperature-dependent properties, enter the negative of number the temperature-dependent property set in place of the constant value. Data for temperature-dependent property sets is defined below.

ITEM	DESCRIPTION	SYMBOL
	Designator (PR)	
	Property set number	NM
1	X-conductivity / temp-depend property set (1)	Kx
2	Specific heat / temp-depend property set (1)	C
3	Lb-mass density / temp-depend property set (1)	m
4	Emissivity	e
5	Thermal conductivity in global y-direction (2)	Ky
6	Thermal conductivity in global z-direction (3)	Kz
7	Coordinate system for conduction properties (4)	MCS

Notes

1) For temperature-dependent properties, set value to NEGATIVE of temperature-dependent property set number.

2) Default Ky=Kx

3) Default Kz=Kx

4) For orthotropic conduction, MCS is the number of the coordinate system that defines the directions of Kx, Ky and Kz. For MCS=0 in 2D problems, Kx and Ky are oriented in the local x and y directions. For 3D problems, with MCS=0, Kx, Ky and Kz are oriented in the global x, y, and z directions.

Temperature-Dependent Thermal Properties

Temperature dependent properties are represented by a polynomial function of temperature:

$$f(t) = a0 + a1*t + a2*t^2 + a3*t^3 + \ldots$$

The coefficients a0, a1, a2, ..., are entered on this proprety set record. From 1 to 8 coefficients may be entered. Trailing null coefficients may be omitted, but intermediate null coefficients must be entered.

Temperature-dependent properties may be specified for the following element properties:

STIF31: K,C,H,m
STIF32: H
STIF33: K,C,m
STIF34: K,C,H,m

STIF35: K,C,m
STIF36: K,C,H,m
STIF37: K,C,m
STIF38: K,C,m
STIF39: K,C,m

where, K:conduction, C:capacitence, m:lb-mass, H:convection

The initial temperature specified on the Solution Control record is required to determine initial property values. Temperature-dependent materials are assumed to be isotropic.

ITEM	DESCRIPTION	SYMBOL
	Designator (PR)	
	Property set number	NM
1	First coefficient	a0
2	Second coefficient	a1
...		...
	Eighth coefficient	a7

3.5.6 Description of LIBRA Files and Post-Processors: AOS Safety Analysis Report

Description of Libra Files and Post-Processors:

AOS Safety Analysis Report

Prepared for: GE-Hitachi Nuclear Energy
PO No. 431004505
May 3, 2007

Prepared by: Structural Mechanics Analysis, Inc.
P.O. Box 700910
San Jose, CA 95170-0910

0.1 Table of Contents

0.2 List of Figures

1.0 Introduction

The Alpha-Omega Services (AOS) Safety Analysis Report (SAR) applies to four radioactive materials Type B cask configurations. These four cask configurations are designated by their relative size as AOS-025, AOS-050, AOS-100, and AOS-165. Configuration AOS-025 is approximately 25% the size of configuration AOS-100, configuration AOS-050 approximately 50%, and configuration AOS-165 approximately 165% in comparison to the AOS-100 model. The following provides a description of the Libra post-processors used to perform the structural and thermal analyses to support the preparation of the SAR for the four AOS cask models.

Notwithstanding the scaled nature of the four configurations, the thermal and stress analyses for the four models are not scalable. Rather, an independent set of analyses is required for each model. While the analyses are not scalable, the finite element models used in the analyses are largely scaled, although there are significant differences between models, particularly between model AOS-165 and the others.

Almost all of the thermal and stress analyses in the SAR are based on application of the Structural Mechanical Analysis, Inc. (SMA) Libra finite element program. The Libra program has been used by GE-Hitachi Nuclear Energy Americas, LLC ("GEH") for a number of years, and was used in the licensing of the Model 2000 Type B transport packaging. SMA has proprietorship of the Libra program, as a result, SMA was able to develop sophisticated post-processing tools integrated with the Libra program, that facilitated the AOS analyses.

The majority of the SAR analyses permit use of axisymmetric, finite element models, since for the majority of load cases the cask, loading, and boundary conditions are axisymmetric. As a result, four axisymmetric models were developed corresponding to the four cask configurations, and these models are the cornerstones of all the finite element analyses in the SAR. For load cases such as drop and transport, where assumptions of axisymmetric loading and boundary conditions are not applicable, 3D finite element models are used. These 3D models are generated from the axisymmetric models by rotation of the model. In this way, there is a well-defined relationship between elements in the axisymmetric and 3D models, and this relationship allows combining stress resultants from the two models.

The two U.S. Nuclear Regulatory Commission (NRC) documents that govern the analyses included in the SAR are Regulatory Guides 7.6 and 7.8. Reg. Guide 7.6 defines the allowable stresses for nuclear shipping casks, while Reg. Guide 7.8 defines the required loading conditions and load combinations. Further, Reg. Guide 7.6 specifies allowable stresses in terms of membrane and bending stresses, or more generally stress resultants. Stress resultants are not a direct output of finite element analyses. For the detailed models used in the AOS analyses, forming stress resultants involves identifying and integrating element stresses across a number selected cask cross-sections. This is an arduous and time consuming task. In addition, NRC Reg. Guide 7.8, which defines the load combinations that must be meet, presents additional difficult tasks for analyses based on the finite element method.

1.0 Introduction - Cont'd

Two major post-processing programs were developed to facilitate evaluation of stress resultants and stress combinations required by NRC Reg. Guides 7.6 and 7.8. The first, PmPb, forms the stress resultants required by Reg. Guide 7.6, while the second, CmbLds, forms the load combinations required by Reg. Guide 7.8. The methodology and application of these programs are described in detail in this report. The solution process for all of the four cask configurations involves first finding stresses corresponding to a set of basic load conditions, and then finding the stress combinations. For thermal loading conditions, one or more thermal solutions must be found before solving for stresses. After determining load case stresses, stress resultants are formed by application of the PmPb post-processing program. The PmPb program generates files containing stress resultants for the basic loading conditions. After all of the loading conditions have been run, and corresponding files of stress resultants generated by PmPb, The CmbLds program is executed. The CmbLds program reads the files generated by PmPb, forms the required combinations, and compares the combined stresses to the allowables in Reg. Guide 7.6. This entire process is automated by a Windows Command program, Run_AOS. A section of the Run_AOS batch program is shown in Appendix F.

2.0 PmPb Post Processor Program

The PmPb program forms the stress resultants referenced by Reg. Guide 7.6. The PmPb is a suite of three programs: PmPbData, PmPb, and PmPb3D. Each of these thee programs is described below. All three programs use the input file PmPb.in, which lists the elements at each model cross-section where stress resultants are evaluated. A sample PmPb.in file is shown in Appendix A.

The cross-sections on which PmPb operates are shown in Figures 1 and 2. Figure 1 shows the cross-sections for model 165, and Figure 2 shows the cross-section for models 025, 050, and 100. Model 165 has 25 stress cross-sections, while models 025,050, and 100 have 22 stress cross-sections. The larger number of cross-sections for model 165 is due to the split outer shell. The elements comprising the cross-sections shown in Figures 1 and 2 are defined on the respective input data file PmPb.dat. The 165 cask axisymmetric, and three dimensional finite element models are shown in Figures 3 and 4, respectively.

2.1 AOS Input Load Case designations

AOS Libra input data files all have designations starting with LCnnn, where nnn is a three digit load case number; and ending with suffix mmm, where mmm is a three digit model number. For example, the input file for thermal load case 101, model 025 is, LC101.025. Additional file description is entered following the load case number, with a hyphen preceding the entry. For example LC101-2500-UPDATE.025 is the designation for input file for thermal load case 101, 2500 watts, updated.

AOS load case numbers define the type of loading involved in the load case. Load cases numbered 101-199 are thermal loadings. Load cases 201-299 are pressure or other axisymmetric normal loadings. Load cases 301-399 are accident condition loadings. The load case types are used by the CmbLds program to determine allowable stress for load combinations.

2.2 PmPbData Program

PmPbData program determines the geometry data for the PmPb program, and stores this data on the file PmPb.dat. This geometry function is separated from the PmPb program for efficiency, as it needs to be performed only once for each model. PmPbData must be executed immediately following an execution of the Libra program, as it uses Libra output. The program reads Libra model geometry data from binary file Tape9, and generates the geometric data required to form membrane and moment stress resultants for each stress cross-section. This data is written to the file PmPb.dat, and is utilized by both PmPb and PmPb3D.

2.3 PmPb Program

The PmPb program generates files of membrane and bending stress resultants for axisymmetric loading conditions. The program utilizes the geometry data on the file PmPb.dat, the cross-section elements defined on PmPb.in, and Libra stress data on the binary file Tape8. PmPb generates output files labeled LOAD_CASE.nnn, where nnn is the load case number. For each LCnnn file there is a corresponding LOAD_CASE.nnn file. A typical output file generated by PmPb is shown in Appendix B. Output files list maximum principal stress, and membrane and bending stress for each cross-section. The PmPb program must be executed immediately following execution of a Libra stress run.

2.4 PmPb3D Program

The PmPb3D program generates files containing membrane and moment stress resultants for 3D loading conditions. The program utilizes the geometry data on the file PmPb.dat, cross-section element data on the file PmPb.in, and Libra stress output on the binary file Tape8. All AOS 3D models are generated from axisymmetric models. As a result, each element along a meridian corresponds to a element in the corresponding axisymmetric model. PmPb3D finds the stress resultants for each element along a meridian, and outputs maximum values on the LOAD_CASE file. Stress combinations involving axisymmetric and 3D load cases conservatively combine maximum meridian 3D values with axisymmetric values. The output of PmPb3D is the same as PmPb, and a typical file shown in Appendix B.

2.5 GroupAllow Program

The GroupAllow program finds maximum temperatures at cross-sections where stress resultants are evaluated, and interpolates temperature-dependent, allowable stress data to find the allowable cross-section stress corresponding to these maximum temperatures. This program is executed only for thermal load cases, and is executed after a Libra thermal solution. The GroupAllow program generates files ALLOWABLES.nnn, where nnn is load case number, and the file is subsequently used by the CmbLds program. A typical GroupAllow output file is shown in Appendix C.

3.0 CmbLds Program

As described in Section 2.3, The PmPb program generates stress resultant files LOAD_CASE.nnn, where nnn is the load case number. The CmbLds program forms load combinations using these files, and also determines the allowable stresses against which the combined stresses are compared. A typical CmbLds.in file is shown in Appendix D.

The load case number nnn in the file name LOAD_CASE.nnn defines the type of loading, as described in Section 2.1. LOAD_CASE.nnn files list both membrane and bending stress for each stress cross-section. The ALLOWABES.nnn files, described in Section 2.5, specify allowable stresses for thermal loadings. Based on all this information, the CmbLds program determines the maximum combined stress, the minimum allowable stress, and the minimum margin of safety at all stress cross-sections. The maximum stresses and minimum allowables are output on the file CmbLds.out. A typical output section generated by CmbLds is shown in Appendix E. The table in Appendix E lists the combined stress, allowable stress, and minimum margins of safety for each cross-section. The overall minimum margin of safety is listed at the end of the table.

4.0 AOS Files

The AOS input and output data files, PMPB verification files, and Libra Program files are contained on a single CD. The folders on this disk are listed below, and the following sections describe the contents of these folders.

aos-25	Input data files for AOS cask Model 025
aos-50	Input data files for AOS cask Model 050
aos-100	Input data files for AOS cask Model 100
aos-165	Input data files for AOS cask Model 165
aos-165-2500	Input data files for AOS cask Model 165, 2500 watts
PMPB_Verification	Verification report for post-processors
Source	Post-processors source code
aos-25-out	Output files for AOS cask Model 025
aos-50-out	Output files for AOS cask Model 050
aos-100-out	Output files for AOS cask Model 100
aos-165-out	Output files for AOS cask Model 165
aos-165-2500-out	Output files for AOS cask Model 165, 2500 watts
drop-25	Files for AOS cask Model 025 30' drop analyses
drop-50	Files for AOS cask Model 050 30' drop analyses
drop-100	Files for AOS cask Model 100 30' drop analyses
drop-165	Files for AOS cask Model 165 30' drop analyses

4.1 Input Data Files

The five input data folders, aos-25 ... aos-165-2500, contain all files required to run the Libra stress and thermal analyses for the five cask models. After establishing the Libra program (see Section 4.5), there is a two step process for executing Libra analyses and post-processing programs for a cask model: 1) copy the entire contents of an input data folder onto the Libra.app, or Libra.app sub-folder, directory; 2) execute the batch program RUN_AOS.

All input data is in English units. For thermal problems temperatures are in degrees F, energy in Btu, and length in inches. For structural problems loads are in lb, moduli in lb/in^2, and length in inches.

Libra executions may take several hours. Output from the Libra runs and post-processors consist of a series of text files labeled Load_Case.nnn, where nnn represents the load case number, and a file labeled Cmb_Loads.out. The Load_Case.nnn files contain the Pm and Pb stress measures at the monitored cask cross-sections for the individual load cases. The Cmb_Loads.out file contains the load combination results, including margins of safety for all combined load cases.

4.2 PMPB Verification Files

The PMPB_Verification folder contains both a report and a verification problem for PMPB and Cmb_Loads post-processors. The verification problem is a simple flat-top cylindrical shell under pressure and thermal loads. The stress resultants as two shell cross-sections are determined analytically, and by the PMPB and Cmb_Loads post processors. The two sets of results are shown to compare well.

A folder containing a set of verification problems for the Libra program, with emphasis on the AOS problem types, is established with installation of the Libra program (see Section 4.5). The Source folder contains the Fortran source codes for the six post processing programs used in the AOS Libra analyses.

4.3 Output Data Files

The AOS-25-out ... AOS-165-2500-out folders contain selected output from the individual Libra load case analyses (see Section 2.1). Each folder contains the LOAD_CASE file (see Section 2.4), The ALLOWABLES file (see Section 2.5), and the Libra output file (TAPE6) for each input data file. The extensions on LOAD_CASE, ALLOWABLES, and TAPE6 files are the same as the input file extension.

4.4 Files for 30' Drop Analyses

The four drop analysis folders, drop-25 ... drop-165, contain input and selected output files for the 30' head-on, side and cg/corner drop analyses. Each folder contains files for a single model, and for the three drop analyses. The output files are plot files for force-energy curves, model displacement, and model stress. The file names have -force,- disp, or -stress to indicate content. File names containing -cold are plots for -40° F thermal conditions, all other files are for 75° F.

The same Libra input data file can be used for all three drop orientations, with non-applicable orientation data commented out by an asterisk in column 1. All of the plot files are BMP format files, and may be viewed by means of the MS Paint program. The displacement and stress files are for displacement fields close to, but not necessarily at maximum values.

The drop-165 folder also contains the Libra input data file slap-down.t5 for slap-down analysis. This file is specifically for AOS model 165 cask, but is easily adapted to other cask models by changing the model structure dimensions and contact stiffness values. Contact stiffness values are taken from the 30' side-drop analyses.

5.0 Libra Installation

Libra installation files are contained in the Libra64 folder. The Libra Program is installed by executing the SETTUP program on the Libra64 folder. The SETUP program will request names for Libra Program and Application directories. Libra program files reside on the Program directory, and problems are executed from the Application directory or sub-directories. Default folder names are Libra64 for the program directory, and Libra.app for the application directory. The SETUP program will also prompt for installation of the 64-bit version of Libra. The 64-bit version should be installed only if the host operating system is 64 bits.

On Vista operating systems it may be necessary to set permission for running Script files before executing the Libra SETUP program. The following steps establish permission:

go to Control Panel
click on User Accounts
click on Turn user control on or off
uncheck user account control

After the Libra SETUP program is completed, the Libra program can be executed from the Start menu, or from the Command line in the Libra application folder. The AOS files are organized to run from the Libra Command line. To access the Libra Command line, left click on the Libra Desktop icon. To then execute a Libra input file, at the Command prompt enter,

```
Libra  input_file  output_file
```

If output_file is omitted, the default file name is TAPE6. After a Libra execution, the model can be viewed by entering HPLOT at the command prompt, and stresses viewed by entering STRSPP. Both HPLOT and STRSPP are menu driven.

To execute a set of AOS analyses on the distribution disk, say \aos-25, read the entire contents of \aos-25 onto the application directory (or sub-directory), then enter run_aos at the Command prompt. This executes the batch program run_aos, which executes all of the files and post-processors for AOS Model 025. Output will be contained on a set of files labeled Load_Case.nnn, and on the file Cmb_Loads.out (see Sections 2.3 and 3.0).

Libra installation establishes a folder labeled Verification. This folder contains a number of verification problems for Libra elements and solution procedures. The thermal problems, and several of the structural problems are directly applicable to AOS analyses. In total, the verification problems in this folder encompass all of the Libra elements and solution procedures applied in the AOS analyses. The verification files described in Section 4.2 address the post-processors used in the AOS analyses, and are an adjunct to these Libra verification problems.

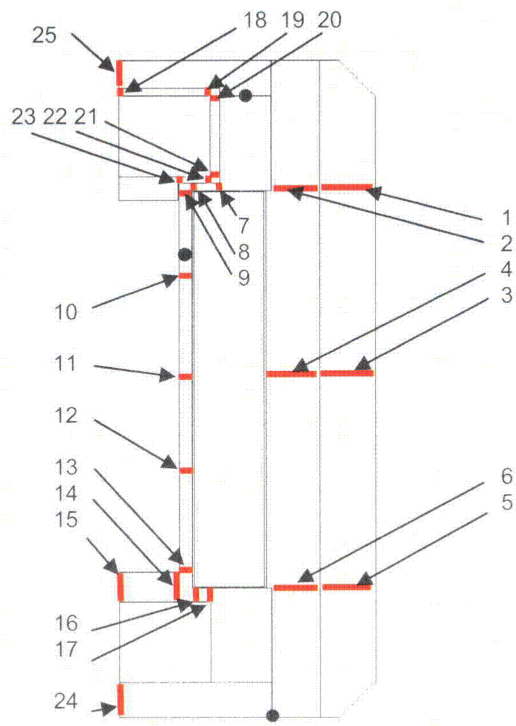


Figure 1. Model 165 PmPb Cross-Sections

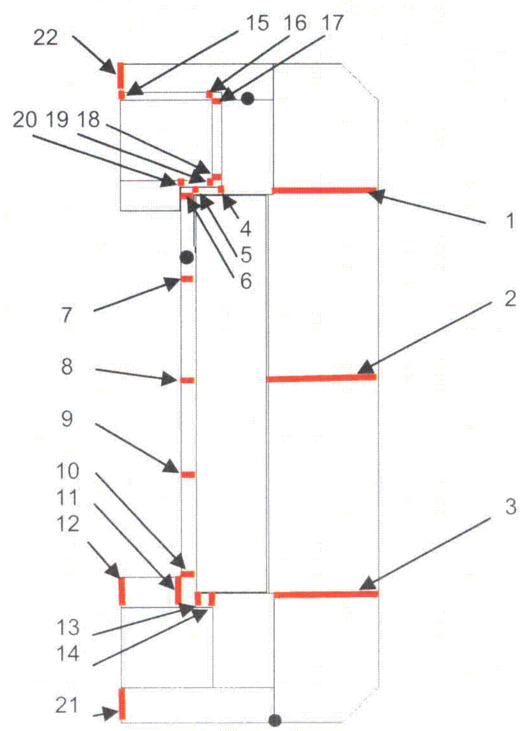


Figure 2. Models 025, 050 and 100 PmPb Cross-Sections

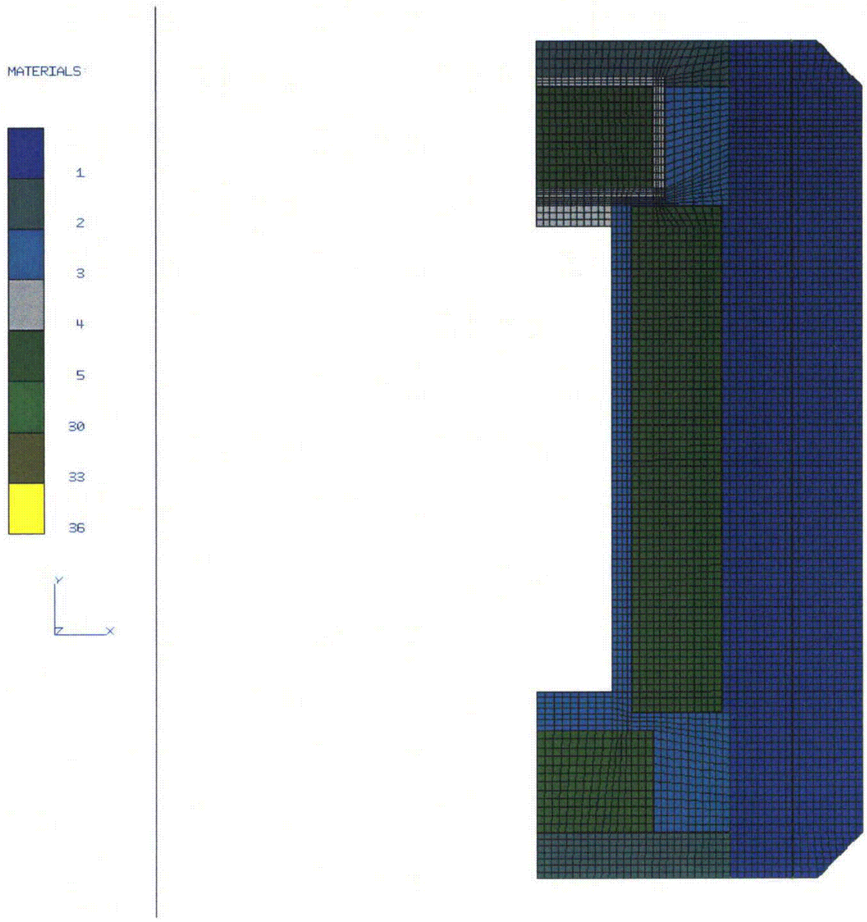


Figure 3. Axisymmetric FEA Model of 165 Cask

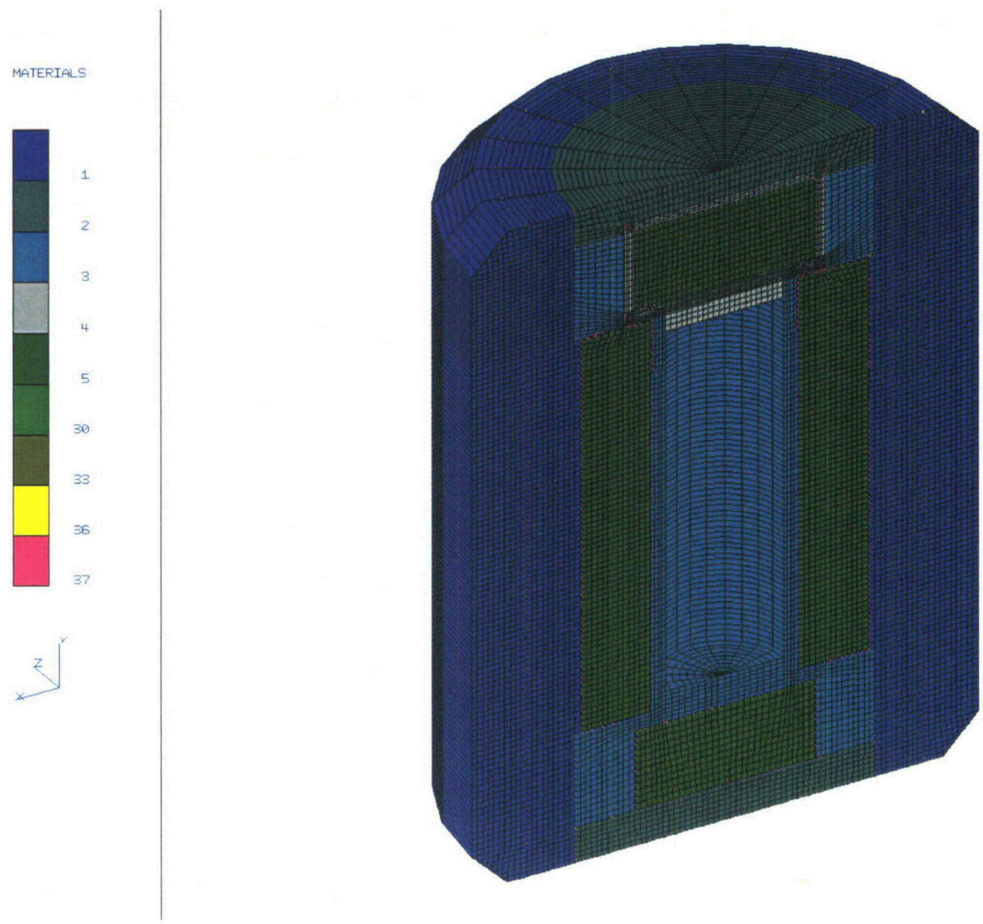


Figure 4. Three Dimensional FEA Model of 165 Cask

Appendix A. Typical PmPb.in File

The following is a typical PmPb.in file listing elements at each stress cross-section. For ease of viewing, cross-section entries are not confined to one line, and blank lines separate entries. In the actual file all section entries are on one line, and there are no blank lines.

```
1957,1958,1959,1960,1961,1962,1963,1964,1965,2146,2147,2148,2149,2150,
2151,2152,2153,2154,2155

552,904,905,906,907,908,909,910,911,912,1587,1588,1589,1590,1591,1592,
1593,1594,1595,1596

348,349,350,351,352,353,354,355,356,507,508,509,510,511,512,513,514,515,
516

4587,4591,4595,4599

4572,4575,4578,4581

552,4553,4554,4555

4476,4477,4478,4479

4408,4409,4410,4411

4344,4345,4346,4347

4280,4281,4282,4283

4141,4150,4159,4168,4177,4186,4195

4133,4142,4151,4160,4169,4178,4187

4212,4215,4218,4221

4214,4217,4220,4223

5218,5236,5254

5235,5253,5271

5214,5215,5216,5217

5166,5167,5168,5169

5140,5143,5146,5149

5122,5126,5130,5134

3001,3017,3033,3049,3065,3081,3097

3190,3208,3226,3244
```

Appendix B. PmPb output file, LOAD_CASE.101

The following is the PmPb output file for load case LC101.025. The file lists maximum principal stresses, and calculated membrane and bending stress at each section analyzed. Stresses are listed in both English and metric units.

Load Case_101 - 100F Ambient, Max Decay Heat

Stress (psi/MPa)

Location	Sigma_1	Sigma_2	Sigma_3	Pm	Pb
1	1.2232E+01	-2.5191E+01	-1.8387E+00	3.7423E+01	5.8177E+01
	8.4340E-02	-1.7369E-01	-1.2677E-02	2.5803E-01	4.0111E-01
2	1.6225E+01	-3.2962E+01	-6.5255E+00	4.9187E+01	1.0016E+02
	1.1187E-01	-2.2727E-01	-4.4992E-02	3.3913E-01	6.9059E-01
3	1.0870E+01	-2.3382E+01	-1.1174E+00	3.4252E+01	5.3526E+01
	7.4943E-02	-1.6122E-01	-7.7043E-03	2.3616E-01	3.6905E-01
4	6.2382E+01	-2.3843E+02	-4.1530E+01	3.0081E+02	5.9563E+02
	4.3011E-01	-1.6439E+00	-2.8634E-01	2.0740E+00	4.1067E+00
5	6.1432E+01	-2.6905E+02	-1.2242E+02	3.3048E+02	5.2038E+02
	4.2356E-01	-1.8550E+00	-8.4406E-01	2.2786E+00	3.5879E+00
6	6.4534E+00	-1.3381E+02	-1.5795E+02	1.4026E+02	1.6725E+02
	4.4494E-02	-9.2256E-01	-1.0890E+00	9.6705E-01	1.1532E+00
7	-1.9752E+00	-4.9672E+01	2.5928E+00	4.7697E+01	4.3899E+01
	-1.3619E-02	-3.4248E-01	1.7877E-02	3.2886E-01	3.0267E-01
8	-2.0037E+00	-4.9648E+01	1.9949E-03	4.7644E+01	4.3457E+01
	-1.3815E-02	-3.4231E-01	1.3755E-05	3.2850E-01	2.9962E-01
9	-1.9811E+00	-4.9582E+01	-5.2273E-01	4.7600E+01	4.1764E+01
	-1.3659E-02	-3.4185E-01	-3.6041E-03	3.2819E-01	2.8795E-01
10	-7.5888E+00	-6.6970E+01	1.0700E+01	5.9381E+01	1.2009E+02
	-5.2323E-02	-4.6174E-01	7.3772E-02	4.0942E-01	8.2802E-01
11	-1.6114E+01	-1.0104E+02	-5.3150E+01	8.4930E+01	7.0193E+00
	-1.1110E-01	-6.9668E-01	-3.6645E-01	5.8557E-01	4.8396E-02
12	4.9440E+00	-1.1870E+02	-1.1938E+02	1.2364E+02	7.5796E+00
	3.4087E-02	-8.1839E-01	-8.2311E-01	8.5248E-01	5.2260E-02

13	-1.3346E+01	-1.7829E+02	-2.9776E+01	1.6495E+02	8.7679E+01
	-9.2016E-02	-1.2293E+00	-2.0530E-01	1.1373E+00	6.0452E-01
14	-1.2832E+01	-1.5680E+02	3.6799E+00	1.4396E+02	9.5911E+01
	-8.8473E-02	-1.0811E+00	2.5372E-02	9.9259E-01	6.6128E-01
15	3.4752E+02	-3.2306E+02	-3.0278E+01	6.7058E+02	1.1250E+03
	2.3960E+00	-2.2274E+00	-2.0876E-01	4.6235E+00	7.7568E+00
16	1.2110E+02	-2.3963E+02	-7.8259E+01	3.6074E+02	5.8708E+02
	8.3498E-01	-1.6522E+00	-5.3958E-01	2.4872E+00	4.0478E+00
17	5.3313E+01	-1.6483E+02	7.7898E+00	2.1815E+02	3.7767E+02
	3.6758E-01	-1.1365E+00	5.3709E-02	1.5041E+00	2.6039E+00
18	1.3652E+01	-8.6978E+01	1.2149E+02	1.0063E+02	1.5144E+02
	9.4130E-02	-5.9969E-01	8.3767E-01	6.9382E-01	1.0442E+00
19	3.7352E+01	-1.4759E+02	9.9594E+01	1.8495E+02	3.1090E+02
	2.5754E-01	-1.0176E+00	6.8668E-01	1.2752E+00	2.1436E+00
20	2.5189E+01	-1.9576E+02	9.1481E+00	2.2095E+02	4.1088E+02
	1.7367E-01	-1.3497E+00	6.3074E-02	1.5234E+00	2.8329E+00
21	6.6491E+00	-2.2294E+00	-1.0467E+00	8.8785E+00	6.0550E+00
	4.5844E-02	-1.5371E-02	-7.2168E-03	6.1215E-02	4.1748E-02
22	2.7655E+00	-1.5235E+01	-3.0961E+00	1.8000E+01	4.4221E+01
	1.9068E-02	-1.0504E-01	-2.1347E-02	1.2411E-01	3.0489E-01

Appendix C. GroupAllow Program Output File

The following is the GroupAllow program output file for load case LC101.025. This file lists maximum and average temperatures at each stress section, and the allowable membrane, yield, and ultimate stress at these sections.

Allowable Stress for Load Case 101

LOC	Tmax (deg_F)	Tave (deg_F)	Sm (ksi)	Sy (ksi)	Su (ksi)
1	138.91	138.74	20.00	30.00	70.00
2	138.94	138.59	20.00	30.00	70.00
3	138.62	138.37	20.00	30.00	70.00
4	139.15	139.13	20.00	30.00	70.00
5	139.61	139.54	20.00	30.00	70.00
6	139.79	139.72	20.00	30.00	70.00
7	140.04	139.89	20.00	30.00	70.00
8	139.99	139.85	20.00	30.00	70.00
9	139.92	139.77	20.00	30.00	70.00
10	139.78	139.64	20.00	30.00	70.00
11	139.92	139.66	20.00	30.00	70.00
12	140.39	140.09	20.00	30.00	70.00
13	139.33	139.20	20.00	30.00	70.00
14	139.04	138.97	20.00	30.00	70.00
15	139.08	139.03	20.00	30.00	70.00
16	139.19	139.14	20.00	30.00	70.00
17	139.22	139.19	20.00	30.00	70.00
18	139.37	139.34	20.00	30.00	70.00
19	139.50	139.44	20.00	30.00	70.00
20	140.26	140.14	20.00	30.00	70.00
21	138.43	138.36	20.00	30.00	70.00
22	138.82	138.76	20.00	30.00	70.00

Appendix D. Typical CmbLds.in File

The following is a typical PmPb.in file. The first entry is the number of stress cross-sections. The next set of entries is the load case numbers, and this set is terminated with a -1. The second and last set of entries are the load combination numbers, and the combination load cases. Text following entries is descriptive, and not used by the program

```
22
101       ; 100F Ambient, Max Decay Heat
102       ; 100F Ambient, Max Decay Heat, Max Insolation
103       ; -20F Ambient, Zero Decay Heat, Zero Insolation
104       ; -40F Ambient, Zero Decay Heat, Zero Insolation
105       ; -40F Ambient, Max Decay Heat
111       ; Fire @ 30 Min, 1475F Ambient, Max Decay Heat
112       ; Fire @60 Min, 100F, Max Decay Heat,Max Insolation
113       ; Fire @90 Min, 100F, Max Decay heat,Max Insolation
114       ; Fire @120 Min, 100F, Max Decay Heat,Max Insolation
115       ; Fire @150 Min, 100F, Max Decay Heat,Max Insolation
116       ; Fire @180 Min, 100F, Max Decay Heat,Max Insolation
201       ; Maximum Internal Pressure, 30 psi
202       ; Minimum External Pressure, 3.5 psia
203       ; Maximum Increased Pressure, 20 psia
204       ; Additional Increased External Pressure, 290 psi
211       ; Fabrication Stress
215       ; Compression Load
216       ; Rod Drop
221       ; Forward 5g Vibration Inertia Load
222       ; Lateral 5g Vibration Inertia Load
223       ; Vertical 10g Vibration Inertia Load
231       ; 4 ft head-on drop
232       ; 30 ft head-on drop, normal conditions
301       ; 30 ft Head-on drop
302       ; 30 ft Side drop + slap-down
303       ; CG/Corner Drop
304       ; 30 ft Head-on drop, low temp
305       ; 30 ft Side drop + slap-down, low temp
306       ; CG/Corner Drop, low temp
311       ; 3 ft drop onto rod
-1
101, 101,201,211          ; hot environment
102, 104,201,211          ; cold environment
103, 103,201,211          ; increaded ex pres
104, 101,201,202,211      ; min ex pres
105, 105,201,202,211      ; cold environment
106, 101,201,203,211      ; max pres, hot environment
107, 105,201,203,211      ; max pres, cold environment
215, 215,101,201,211      ; compression load
216, 216,101,201,211      ; rod drop
217, 216,104,201,211      ; rod drop cold environment
221, 221,101,201,211      ; fwd vibration
222, 222,101,201,211      ; lateral vibration
```

```
223, 223,101,201,211     ; vertical vibration
231, 231,102,201,211     ; 4 ft head-on drop, normal conditions
232, 232,102,201,211     ; 30 ft head-on drop, normal conditions
301, 301,102,201,211     ; head-on drop
302, 302,102,201,211     ; side drop
303, 303,102,201,211     ; cg/corner drop
304, 304,105,202,211     ; head-on drop, cold environment
305, 305,105,202,211     ; side drop, cold environment
306, 306,105,202,211     ; cg/corner drop, cold environment
310, 204,101,211         ; add ext pres (290 psi)
311, 311,101,201,211     ; 3 ft drop onto rod
312, 311,104,201,211     ; 3 ftdrop onto rod, cold environment
350, 111,201,211         ; fire @ 30 min
351, 112,201,211         ; fire @ 60 min
352, 113,201,211         ; fire @ 90 min
353, 114,201,211         ; fire @ 120 min
354, 115,201,211         ; fire @ 150 min
355, 116,201,211         ; fire @ 180 min
-1
```

Appendix E. Typical Output from CmbLds Program

The following is a typical output file from the CmbLds program. The load combination is listed at the top of the table. The file lists maximum membrane and bending stress, and minimum allowables at each section analyzed. Stresses are listed in both English and metric units. Minimum MS and associated values are listed at the end of the table.

```
Normal Load Combination  101
----------------------------
Load Cases: 101 201 211
100F Ambient, Max Decay Heat
Maximum Internal Pressure - 30 Psia
Fabrication Stress


                           Stress (ksi/MPa)
                           ----------------

Loc      Pm       Pb       Q    Pm+Pb  Pm+Pb+Q      Sm       Su      MS
---      --       --       -    -----  -------      --       --      --
  1    0.75     1.10    0.04     1.85     1.89   20.00    70.00    >10
       5.16     7.60    0.26    12.75    13.01  137.90   482.63

  2    0.14     0.20    0.05     0.34     0.38   20.00    70.00    >10
       0.96     1.35    0.34     2.31     2.65  137.90   482.63

  3    0.08     0.08    0.03     0.16     0.20   20.00    70.00    >10
       0.58     0.54    0.24     1.12     1.36  137.90   482.63

  4    1.16     1.78    0.30     2.94     3.24   20.00    70.00   9.20
       8.00    12.28    2.07    20.28    22.35  137.90   482.63

  5    1.18     1.00    0.33     2.18     2.51   20.00    70.00    >10
       8.17     6.88    2.28    15.05    17.32  137.90   482.63

  6    0.78     1.17    0.14     1.95     2.09   20.00    70.00    >10
       5.40     8.05    0.97    13.44    14.41  137.90   482.63

  7    0.34     0.07    0.05     0.40     0.45   20.00    70.00    >10
       2.34     0.45    0.33     2.79     3.12  137.90   482.63

  8    0.32     0.04    0.05     0.36     0.41   20.00    70.00    >10
       2.21     0.27    0.33     2.48     2.81  137.90   482.63

  9    0.36     0.07    0.05     0.43     0.48   20.00    70.00    >10
       2.48     0.48    0.33     2.97     3.29  137.90   482.63

 10    1.23     0.15    0.06     1.38     1.44   20.00    70.00    >10
       8.49     1.03    0.41     9.52     9.93  137.90   482.63
```

11	0.93	1.23	0.08	2.17	2.25	20.00	70.00	>10
	6.44	8.51	0.59	14.95	15.53	137.90	482.63	
12	1.01	1.49	0.12	2.50	2.62	20.00	70.00	>10
	6.95	10.27	0.85	17.23	18.08	137.90	482.63	
13	1.19	1.05	0.16	2.24	2.40	20.00	70.00	>10
	8.21	7.23	1.14	15.44	16.58	137.90	482.63	
14	1.21	1.54	0.14	2.75	2.89	20.00	70.00	9.91
	8.36	10.61	0.99	18.97	19.96	137.90	482.63	
15	1.70	1.94	0.67	3.64	4.31	20.00	70.00	7.25
	11.69	13.38	4.62	25.07	29.70	137.90	482.63	
16	1.70	2.69	0.36	4.39	4.75	20.00	70.00	5.83
	11.72	18.55	2.49	30.27	32.75	137.90	482.63	
17	1.12	1.79	0.22	2.90	3.12	20.00	70.00	9.33
	7.71	12.31	1.50	20.02	21.52	137.90	482.63	
18	0.87	1.40	0.10	2.27	2.37	20.00	70.00	>10
	5.99	9.65	0.69	15.64	16.33	137.90	482.63	
19	1.46	2.17	0.18	3.63	3.82	20.00	70.00	7.26
	10.09	14.96	1.28	25.05	26.33	137.90	482.63	
20	1.82	2.90	0.22	4.72	4.95	20.00	70.00	5.35
	12.58	19.99	1.52	32.57	34.09	137.90	482.63	
21	0.32	0.44	0.01	0.76	0.77	20.00	70.00	>10
	2.24	3.00	0.06	5.24	5.30	137.90	482.63	
22	0.46	0.47	0.02	0.93	0.95	20.00	70.00	>10
	3.20	3.23	0.12	6.43	6.55	137.90	482.63	

Min MS: 5.350, Location: 20, Combination: Pm+Pb

Appendix F. Typical Section of Batch Program to Execute AOS Load Cases

The AOS input data files and post-processor executions are organized and run by a Command batch program. A separate batch program is required for each of the four model configurations. A section of a typical batch program is shown below. Note that the program PmPbData is run before the first execution of PmPb. The GroupAllow program is only run after a Libra thermal analysis. The PmPb (or PmPb3D) program is run after each Libra stress analysis. Calls to the Libra program include the input file name, output file name, and a flag set to 1 to prevent Libra pausing after execution.

```
rem load case 101
call libra lc101-t-update.025  tape6 1
call libra lc101-update.025  tape6 1
groupallow lc101-update.025
pmpbdata
pmpb

rem load case 102
call libra lc102-t-update.025  tape6 1
call libra lc102-update.025  tape6 1
groupallow lc102-update.025
pmpb

rem load case 103
call libra lc103-t-update.025  tape6 1
call libra lc103-update.025  tape6 1
groupallow lc103-update.025
pmpb

rem load case 104
call libra lc104-t-update.025  tape6 1
call libra lc104-update.025  tape6 1
groupallow lc104-update.025
pmpb

rem load case 105
call libra lc105-t-update.025  tape6 1
call libra lc105-update.025  tape6 1
groupallow lc105-update.025
pmpb

rem load case 106
call libra lc106-t-update.025  tape6 1
call libra lc106-update.025  tape6 1
groupallow lc106-update.025
pmpb
```

3.5.7 Properties of Materials References

This appendix provides information related to the following materials:

- Contact Resistance
- Decay Heat
- Stainless Steel (SS304)
- Tungsten Alloy
- General Plastics LAST-A-FOAM
- Air Properties
- Port Seal
- Lid Seal

A list of References is also included.

Contact Resistance

Contact Resistance

- Surfaces with 0.0 clearance.
- All contact surfaces are assumed low a resistance (approximately 30 psi) and have a value of:

$$1/h_c = 0.03\ \frac{hr\text{-}ft^2{}^\circ F}{Btu} \qquad h_c = 0.231\ Btu/hr\text{-}in^2{}^\circ F$$

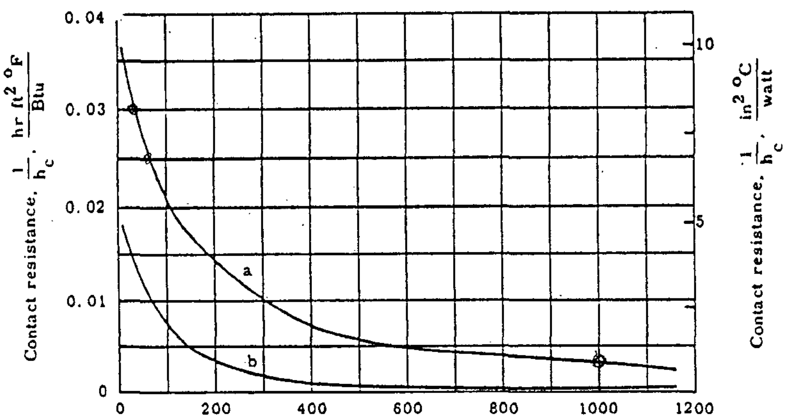
The exception is the shrinkfit surface at the outside shell, where the contact pressure is approximately 2 ksi.

$$1/h_c = 0.003\ \frac{hr\text{-}ft^2{}^\circ F}{Btu} \qquad h_c = 2.315\ Btu/hr\text{-}in^2{}^\circ F$$

STEEL, BARE SURFACES AT HIGH CONTACT PRESSURES (0 to 1200 psi) - Solid blocks in air at reduced pressure ($p < 0.1$ atm)

For steel with bare surfaces in air, see pages 5-6.
For steel with sandwich material in air, see page 8.
For steel in other gases, see page 9.
For steel with dissimilar metal in air, see page 20; at reduced pressure ($p < 0.1$ atm), see page 21.
For other metals in air, see pages 10-11, 17; at reduced pressure ($p < 0.1$ atm), see pages 12-13, 18-19.
For laminated steels in air, see page 23.

Curve	Material[4]	Finish	Roughness Rms (μ in.) Block 1	Roughness Rms (μ in.) Block 2	Fluid in Gap	Temp (°F)	Condition	Ref. No.[5]
a	Stainless Steel 304	Ground	42-60	43-48	Air	75	Clean, 10^{-4} mm Hg abs	45
b	Stainless Steel 304	Ground	15-15	10-10	Air	84	Clean, 10^{-4} mm Hg abs	45



Contact pressure, lb/sq in.

$\frac{1}{h} = 0.03 * 144 = 4.32 \rightarrow h = .231$

[4-5] See page 24

The decay heat of the cask contents is introduced in the model by two-node convective boundary elements along the cask cavity wall. In the model, it is assumed that the load is uniformly distributed over the entire cavity surface.

Convective boundary elements define the convective and radiative properties at the interface between the impact limiter outer surface and the regulatory environments. Another convective surface is located on the side of the cask's outer shell, between the upper and lower impact limiter structures. In addition to convective and radiative properties, these boundary two-node elements have the capability to include required solar heat flux loads.

Figure 3-2 illustrates all components and interfaces of the thermal model.

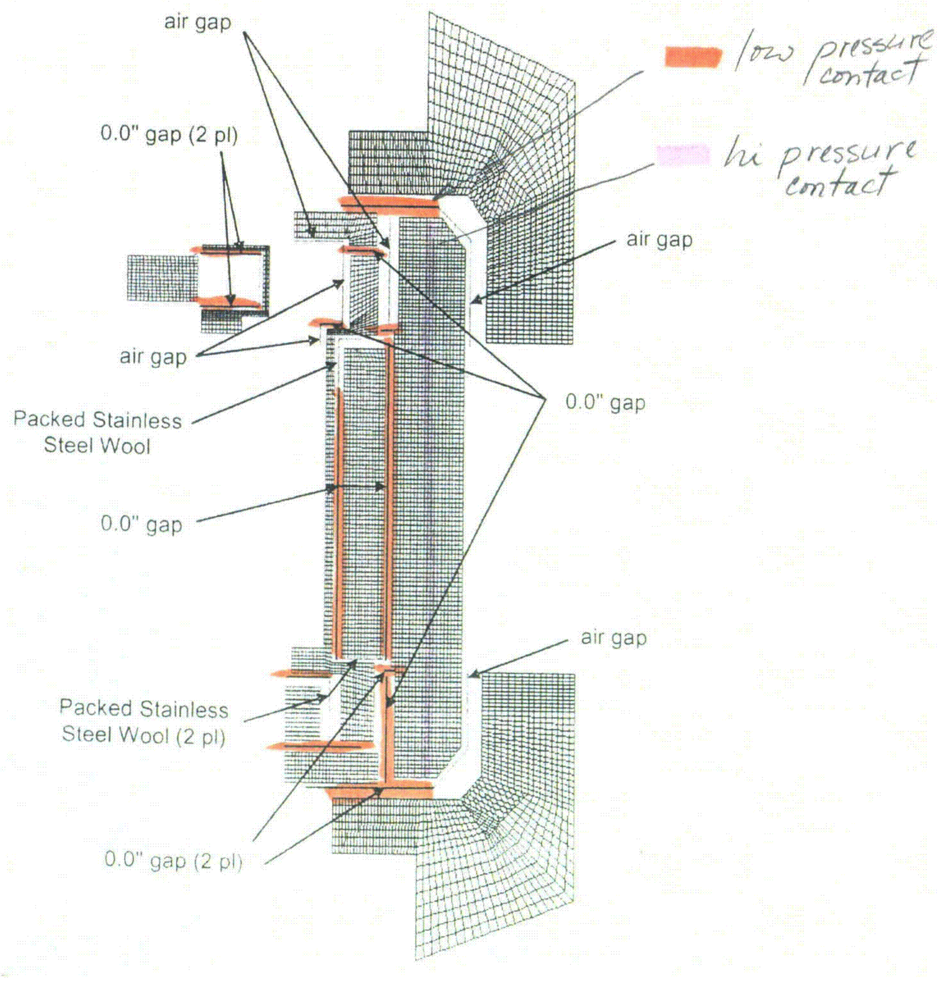


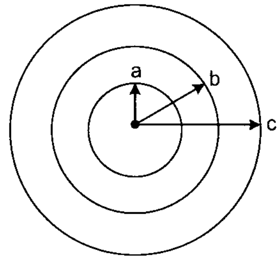
Figure 3-2. Expanded View of Thermal Model Defining Component Interfaces

Shrinkfit

1/13/06

Reference – Shigley, Joseph Edward, *Mechanical Engineering Design*, McGraw Hill Companies, 3rd Ed., 1977.

$$P = \frac{E\delta}{b}\left[\frac{(c^2 - b^2)(b^2 - a^2)}{2b^2(c^2 - a^2)}\right]$$



where:

a	=	13.2 and 13.7
b	=	18.1
c	=	23.1
E	=	$28.3 * 10^6$
δ	=	0.02

$$P_1 = \left(\frac{28.3 * 10^6 * 0.02}{18.1}\right)\left[\frac{(23.1^2 - 18.1^2)(18.1^2 - 13.2^2)}{(2 * 18.1^2)(23.1^2 - 13.2^2)}\right]$$

$$= (0.031271 * 10^6)\left[\frac{(206)(153.37)}{235466.41}\right]$$

$$= 4{,}196 \text{ psi}$$

$$P_2 = 31271\left[\frac{(206)(18.1^2 - 13.7^2)}{(2 * 18.1^2)(23.1^2 - 13.7^2)}\right]$$

$$= 31271\left[\frac{(206)(139.92)}{226654}\right]$$

$$= 3{,}977 \text{ psi}$$

for δ = 0.01 in.

P ~ 2,000 psi

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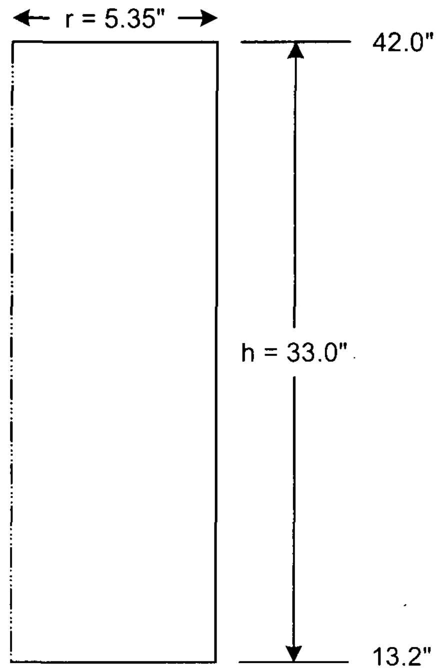
Decay Heat

Decay Heat

Cask Radius and Height – Model AOS-165



$$A = 2\pi\,(5.36)^2 + 2\pi\,(5.36)\,(33.0)$$

$$= 1{,}291.88 \text{ in}^2$$

Heat Flux at Inside Cask Surface

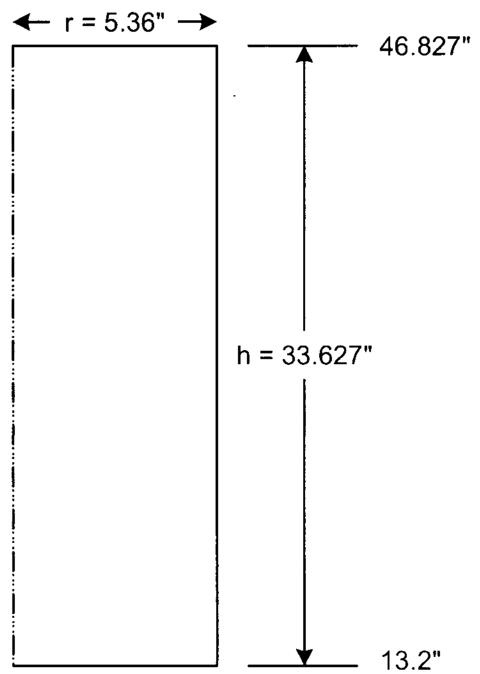
$$q = 23{,}666.3 / 1{,}291.88 = 18.319 \text{ Btu/hr-in}^2$$

Decay Heat Load

450,000 Curies = 6,936W = 23,666.3 Btu/hr

(64.88c = 1W)

Cask Surface Area – Model AOS-165



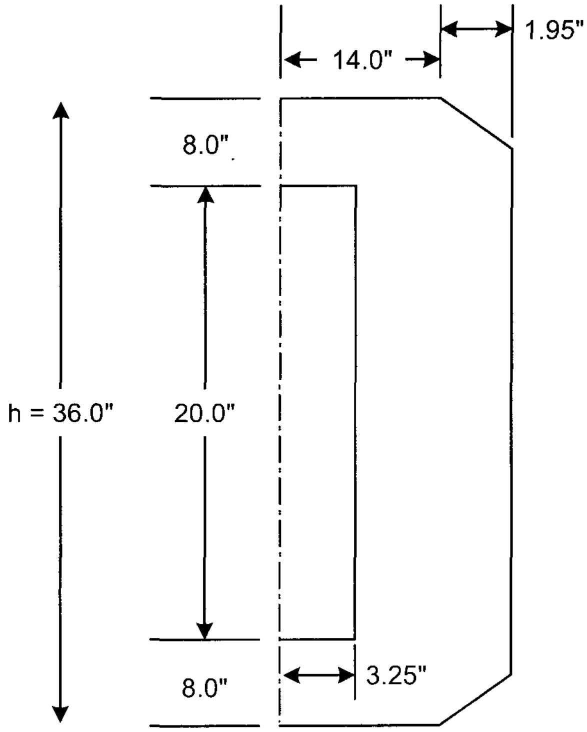
$$A = 2\pi\,(5.36)^2 + 2\pi\,(5.36)\,(33.627) = 1{,}313.0\ \text{in}^2$$

Heat Flux @ Inside Cask Surface

$$q = 23{,}666.3 / 1{,}313.0 = 18.02\ \text{Btu/hr-in}^2$$

Model AOS-100 Cask

Outside Cask Body and Cask Height – Model AOS-100



Decay Heat = 400W

400W = 3.4121 * 400 = 1,365 Btu/hr

Cavity Surface Area

$2\pi\ (3.25^2 + ((3.25)\ (20))) = 474.77\ in^2$

Heat Flux

$1{,}365\ /\ 474.77\ in^2 = 2.88\ Btu/hr\text{-}in^2$

Model AOS-050 Cask

Decay Heat = 100W

$$100W = 3.4121 * 100 = 341.21 \text{ Btu/hr}$$

Cavity Area

$$2\pi\ (1.62424^2 + 1.62424 * (14.0 - 4.0))$$

$$= 118.63 \text{ in}^2$$

Heat Flux

$$341.21 / 118.63 = 2.876 \text{ Btu/hr-in}^2$$

Model AOS-025 Cask

Decay Heat = 10W

Heat Flux

$$(3.4121 * 10) / (2\pi)\ (0.812^2 + ((0.812)\ (7.0 - 2.0)))$$

$$= 1.151 \text{ Btu/hr-in}^2$$

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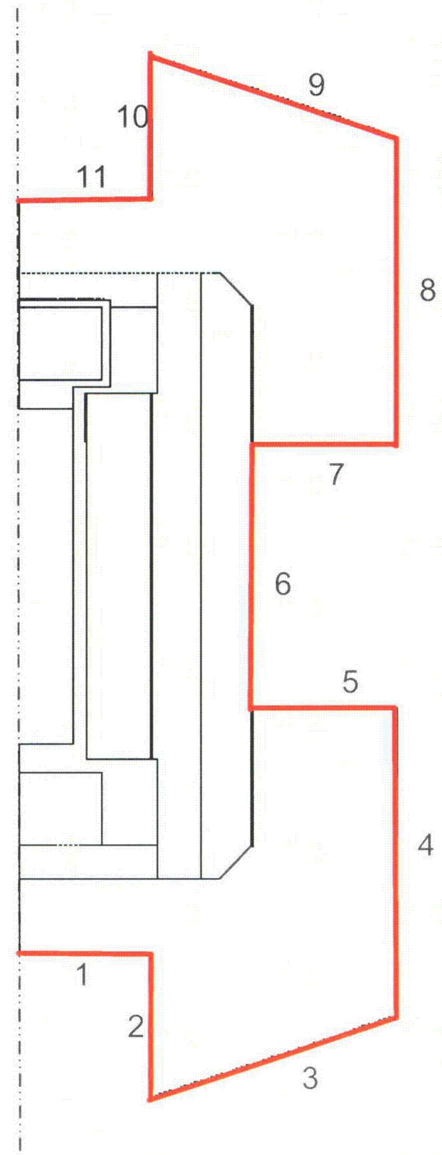
Insolation

Treat surfaces as follows:

Cask Assembly External Surface Identification



1 cal/cm^2 = 0.0256 Btu/in^2

Horizontal Surface	Total Insolation (cal/cm^2)	(Btu/in^2)	Heat Rate BTU/hr-in^2
1, 11	200	5.12	0.4267
2, 10	400	10.24	0.8533
3, 9	400	10.24	0.8533
4, 8	400	10.24	0.8533
5, 7	200	5.12	0.4267
6	400	10.24	0.8533

Stainless Steel (SS304)

2.3 MECHANICAL PROPERTIES OF MATERIALS

The transport package is fabricated from pig lead per Federal Specification QQ-L-171e and 304 stainless steel per ASTM A240. The mechanical properties used in the structural analysis are listed in Tables 2.3.1 and 2.3.2.

TABLE 2.3.1. MECHANICAL PROPERTIES OF LEAD[2.11.7]

Temp. (°F)	$E:10^6$(psi)	μ	$\alpha:10^{-6}$(1/°F)	ρ(Lbm/in.^{3})[2.11.8]	σ_y(psi)[2.11.9]
-50	-	0.43	13.94	0.4097	810
-40	2.58		-		795
75	2.41		16.0		620
100	2.38		16.025		580
150	2.30		16.12		550
200	2.21		16.26		505
250	2.14		16.46		495
300	2.04	0.43	16.7	0.4097	390

TABLE 2.3.2. MECHANICAL PROPERTIES OF STAINLESS STEEL[2.11.10]

Temp. (°F)	$E:10^6$(psi)	μ	$\alpha:10^{-6}$(1/°F)	ρ(Lbm/in.^{3})[2.11.11]	$\sigma_y:10^3$(psi)
-100	29.4	0.30	7.35	0.29	-
70	28.3		-		-
100	-		8.03		30.0
200	27.7		8.20		25.0
300	27.1		8.37		22.5
400	26.6	0.30	8.54	0.29	20.7

TABLE 2.3.3. MECHANICAL PROPERTIES OF BOLTS

Bolt Size/ASTM Standard	Stress Area (in.^{2})	Min. Tensile Strength (ksi)	Yield Strength (ksi)
1.25-7 UNC-2A Socket Head/[2.11.12] ASTM A540, GR B-22 Class 3	0.969	145	130
7/8-9 UNC-2A Shoulder Screw/ ASTM A540, GR B-22 Class 3	0.462	145	130
1-8 UNC-2A Hexagonal Head/[2.11.13] ASTM A193-B6	0.606	110	85

2.11 REFERENCES

1. Code of Federal Regulations, Title 10, Part 71, 1983.

2. U.S. NRC Regulatory Guide 7.6, "Design Criteria for the Structural Analysis of Shipping Cask Containment Vessels".

3. U.S. NRC Regulatory Guide 7.8, "Load Combinations for the Structural Analysis of Shipping Casks", Table 10.

4. W. R. Holman and R. T. Langland, "Recommendations for Protecting Against Failure by Brittle Fracture in Ferritic Steel Shipping Containers Up to Four Inches Thick", Lawrence Livermore Laboratory; Livermore, California; August, 1981; NUREG/CR-1815.

5. ASME, Boiler and Pressure Vessel Code, Section III, Division I, Appendix 1, 1980, Figure I-9.2.

6. Bruhn, E. F., "Analysis and Design of Flight Vehicle Structures", Tri-State Offset Company, Cincinnati, 1965.

7. W. Hoffman, "Lead and Lead Alloys", English Translation of the Second Revised German Edition, Springer-Verlag, New York-Heidelberg-Berlin, 1970.

8. Heat Transfer Data Book, D. A. Kaminski, Ed., General Electric Company, NY, 1981, Sct. G515/29, p. 5.

9. Tietz, E. Thomas, "Determination of the Mechanical Properties of a High Purity Lead and a 0.05% Copper-Lead Alloy", Stanford Research Institute; Menlo Park, California; April, 1958; WADC Technical Report 57-695, ASTIA Document No. 151165.

10. ASME, Boiler and Pressure Vessel Code, Section III, Division 1, Appendix 1, 1980.

11. The International Nickel Company, Inc.; Mechanical and Physical Properties of Austenitic Chromium-Nickel Stainless Steels at Ambient Temperature, 3rd Edition, New York, 1963.

3.2.2 Stainless Steel (304 Type)

TABLE 3.2.2.1. THERMOPHYSICAL PROPERTIES[3.7.4]

Temp.	k(Btu/hr-ft-°F)	α(ft2/hr)
70	8.6	0.151
100	8.7	0.152
200	9.3	0.156
300	9.8	0.160
400	10.4	0.165
500	10.9	0.170
600	11.3	0.174
700	11.8	0.179
800	12.2	0.184
900	12.7	0.189
1,000	13.2	0.194
1,100	13.6	0.198
1,200	14.0	0.203
1,300	14.5	0.208
1,400	14.9	0.212
1,500	15.3	0.216

Conductivity, K (Btu/hr-in.-°F)

$$K(T) \Big|_{70°F}^{1,500°F} = 7.0287 \times 10^{-1} + 3.8987 \times 10^{-4} T$$

Thermal Diffusivity, α (in.2/hr)

$$\alpha(T) \Big|_{70°F}^{1,500°F} = 21.110 + 6.7346 \times 10^{-3} T$$

Density, p (lb/in.3)

$$\rho(T) \Big|_{70°F}^{1,000°F} = 0.29$$

Specific Heat, Cp (Btu/lb-°F)

$$Cp(T) = K(T)/\alpha(T)(\rho)$$

$$Cp(T) \Big|_{70°F}^{1,000°F} = K(T)/(6.1219 + 1.953 \times 10^{-3} T)$$

3.7 REFERENCES

1. Touloukian, Y. S., Thermophysical Properties of Matter, Purdue University, 1970, Vol. 1, p. 191.

2. Ibid, Vol. 4, p. 115.

3. Heat Transfer Data Book, D. A. Kaminski, Ed.; General Electric Company, New York, 1981, Sct. G515.29, p. 5.

4. ASME, Boiler and Pressure Vessel Code, Section III, Division I, Appendix 1, 1980.

5. Kreith, F., Principles of Heat Transfer, International Textbook Company, Pennsylvania, 2nd Ed., 1969, Table A-3.

6. Ibid, Table A-1.

7. Gebhart, B., Heat Transfer, McGraw-Hill Book Company, New York, 2nd Ed., 1971, p. 377.

8. Ibid, p. 355.

9. Ibid, p. 376.

10. Kreith, F., Principles of Heat Transfer, International Textbook Company, Pennsylvania, 2nd Ed., 1969, Table 5-2.

11. Heat Transfer Data Book, D. A. Kaminski, Ed.; General Electric Company, New York, 1981, Sct, G515.5, p. 13.

12. Gebhart, B., Heat Transfer, McGraw-Hill Book Company, New York, 2nd Ed., 1971, p. 371.

13. Kreith, F., Principles of Heat Transfer, International Textbook Company, Pennsylvania, 2nd Ed., 1969, p. 340.

14. Regulatory Guide 7.8, Load Combinations for Structural Analysis of Shipping Casks, U.S. Nuclear Regulatory Commission; May, 1977; Table 1.

15. D. R. Smith and R. H. Jones, "GE Model 1500 Shipping Package Heat Test for Thermal Benchmarking", GE Vallecitos Nuclear Center, NEDO-24899; April, 1981.

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Tungsten Alloy

ATI Firth Sterling
Allegheny Technologies

1297 County Line Road, Madison, AL 35756

Date: 8 November 2006

To: Alpha-Omega Services, Inc.
GE Energy

Elevated Temperature Material Characterization

-- Summary of Findings --

Abstract

Summarized herein are the results of specific thermal property tests performed with SD180 as requested by the customer. Elevated temperature tensile testing of this alloy identified a gradual decrease in both offset yield strength and UTS with increasing temperature whereas the elongation at failure rose sharply and then leveled off. Thermal conductivity testing was inconclusive, as thermal testing firms now utilize laser flash diffusivity measurement, which has been shown to provide unreliable results for this material.

Background

ATI Firth Sterling tungsten heavy alloy (WHA) grade SD180 was selected for use in a new large scale design of gamma shield. This alloy has a nominal composition of 95W-3.57Ni-1.43Fe and a nominal density of 18.0 g/cc. The intensity of the gamma flux will result in significant heating of the shield, such that elevated temperature material properties are of significant interest. As a result, this application requires that the shielding material possess a multiplicity of attributes:

- adequate strength and ductility
- good γ radiation attenuation
- sufficient thermal conductivity

The customer specified the tests and the temperatures at which measurements should be made. Temperatures of interest were ambient, 200F, 400F, 600F, and 800F. Further, so as to match the application, testing was to be performed in air. As ATI Firth Sterling is presently equipped only for room temperature material characterization, elevated temperature testing was contracted out to two selected testing firms.

Experimental

Elevated Temperature Tensile Testing

Tensile Testing Metallurgical Lab (Cleveland, OH) was selected to perform the required elevated temperature tests. Tensile testing was conducted using ASTM E8 1" gauge length specimens pulled at a constant speed of 0.05 in/min. The notch sensitivity of WHA precluded the use of scribe lines or grooves for positioning of a high temperature extensometer. Therefore, crosshead motion was used to generate the displacement measurements in this low compliance, lead screw testing machine. For comparison purposes, a pair of room temperature tensile tests was also performed at ATI Firth Sterling using the same test parameters but with a servohydraulic machine and extensometer. Two specimens were pulled for each test temperature. Averaged results are shown in Table 1.

Table 1. Summary of tensile testing results for SD 180 lot 1808..

Test Temperature	UTS (ksi)	0.2% YS (ksi)	EL (%)
RT (ATIFS)	114.0	93.9	5.0
RT (TTML)	109.7	94.3	3.5
200F (TTML)	112.4	70.8	15.5
400F (TTML)	105.2	60.2	21.8
600F (TTML)	98.2	51.9	21.9
800F (TTML)	95.4	47.8	21.6

The data pairs for each temperature exhibited good agreement, suggesting test results were free from anomalies.

Thermal Property Measurement

Anter Laboratories (Pittsburgh, PA) was selected for measurement of thermal diffusivity and specific heat at the various temperatures of interest. Anter specified that a single disk sample of 0.500" nominal diameter and 0.140" nominal thickness with parallel surfaces and known density be supplied. A SD180 sample from lot 1748 giving a measured ASTM B311 density of 18.11 g/cc was prepared and supplied by ATIFS. Measurements were conducted per ASTM E1461-01. Results are presented in Table 2.

Table 2. Summary of thermal property evaluation of SD 180 lot 1748.

Test Temperature Nom. (F)	Actual (C)	Diffusivity (cm^2/sec)	Specific Heat (J/(kg-K))	Conductivity (W/m-K)
RT	25	0.2742	154.7	76.8
200	97	0.2700	159.2	77.8
400	206	0.2624	163.4	77.6
600	316	0.2553	170.3	78.8
800	427	0.2451	173.9	77.2

The thermal conductivity remained relatively constant over the entire test temperature range, whereas specific heat showed a gradual increase and thermal diffusivity a slow decrease. The room temperature density was applied to all conductivity calculations, as the very low CTE of WHA (less than 5.0×10^{-6} K^{-1}) would result in a change of calculated value of only 0.5 W/m-K or less even at the highest test temperature. This was a factor of 4 less than the reported uncertainty of the test procedure.

Discussion of Results

In reviewing the tensile data set generated, the most pronounced effect was that of moving above the ductile to brittle test temperature (DBTT) for WHA, which in most metallurgical conditions is in the vicinity of room temperature. This accounts for the significant increase in alloy ductility, as measured by %EL. Accompanying this increase in ductility was a gradual decrease in both the ultimate and offset yield strengths, which is to be expected in light of induced thermal effects on various dislocation mechanisms that determine deformation response under load. These effects can be seen clearly when the data of Table 1 are plotted and displayed in Figure 1.

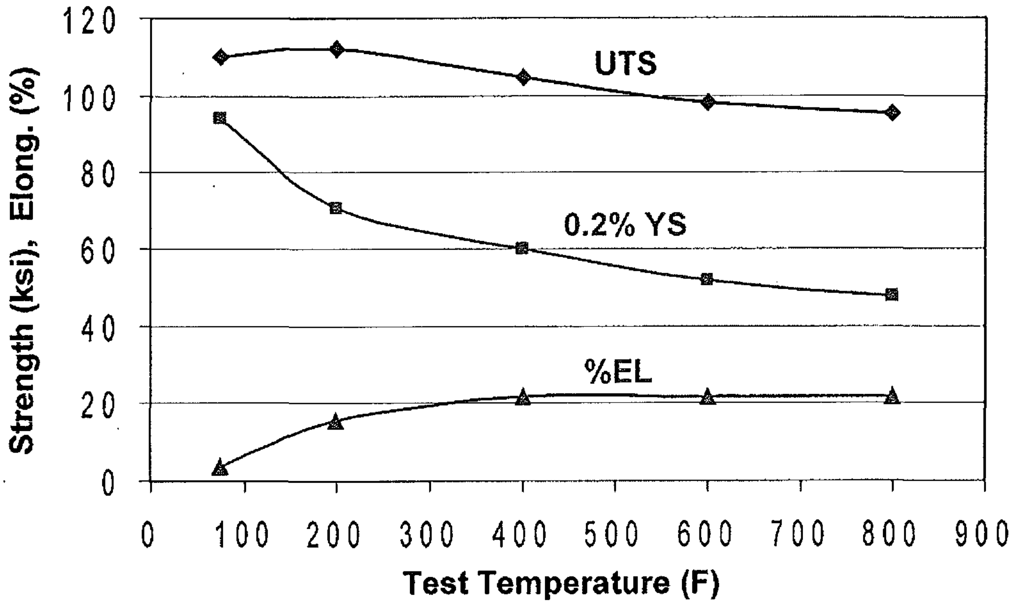


Figure 1. Graphical display of tensile property variation with test temperature.

While the strength of the gamma shield would decrease slightly with heating, the durability of the shield would tend to increase, depending on the magnitude of temperature rise attained.

The data set obtained from thermal property evaluation exhibited consistent trends. However, the resultant calculated values for thermal conductivity, which averaged 78 W/m-K, were well below the accepted industry values for this composition class of WHA. The literature for about two decades has reported values in the range of 110-130 W/m-K. This range is much more in keeping with an alloy having 95 wt.% of a metal that has a conductivity of ~160 W/m-K and is present as a virtually pure phase in the two phase WHA microstructure. The reason for the low measured values is presently unknown. The results obtained appear to underestimate the accepted thermal conductivity by about 35%. Dialogue with Anter revealed no apparent test execution problems. The data set obtained from Anter Laboratories did show that for the temperature range of interest, the thermal conductivity of the WHA, though of systematically low magnitude, did not vary significantly. It was decided that a second independent test be conducted in an effort to understand these results relative to industry accepted values.

Supplemental Testing

In view of the question posed from thermal conductivity testing of the SD180 alloy, a second test sample was prepared for submission to a different laboratory for analysis. While

Anter is nationally recognized for both thermal analysis and the manufacture of thermal analyzers, it was desirable to have a completely independent measurement made. Raul Pomares forwarded the firm of M & P Lab, in that they performed thermal measurements for GE Energy in the past. However, when their thermal analysis contact M. B. Bolduc was contacted, it was learned that they do not perform any thermal conductivity measurements. Harrop likewise, while performing other thermal measurements, does not perform conductivity measurement. Netzsch was therefore chosen as the second source for SD180 thermal conductivity measurement. Netzsch indicated that they also use the laser flash method per ASTM E1461 and calculate the thermal conductivity from measured diffusivity. After about a 6 week lead time, the room temperature test was completed and is shown in Table 3. Netzsch used a density of 18.0 g/cc for the calculation, whereas our measurement yielded 18.06 g/cc.

Table 3. Second conductivity evaluation of grade SD 180.

Test Temperature Nom. (F)	Actual (C)	Diffusivity (mm^2/sec)	Specific Heat (J/(g-K))	Conductivity (W/m-K)
RT	25	16.6	0.153	45.9

This new value for thermal conductivity was even further away from the expected value based on composition and density. This measurement underestimated the accepted average conductivity by at least 60%. After obtaining this margin of error, testing was halted, as any elevated temperature values would likewise be of no value.

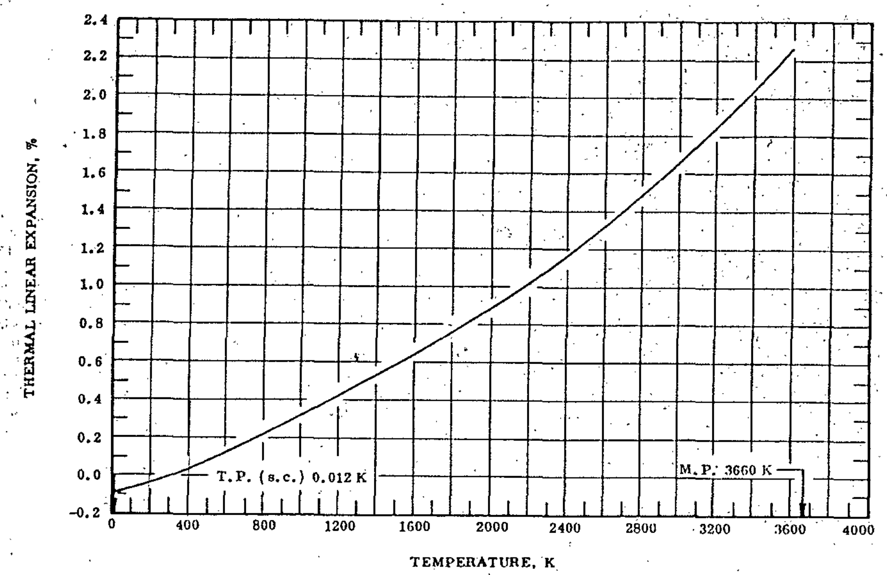
Conclusions

The selected elevated temperature characterization of SD180 provided a more comprehensive prediction of alloy performance in the target application. The identified property trends were in keeping with fundamental elevated temperature response of metallic materials. Excellent ductility was retained over the entire range of test temperature.

Thermal conductivity measurements however were inconclusive. Two independent tests – both using nationally recognized testing firms that not only routinely perform toll thermal testing but also actually manufacture the equipment – failed to provide results that were even in approximate agreement or close to the accepted values used for decades within the refractory metals industry. These low values should therefore be disregarded, as they cannot be independently repeated. As the entirety of this testing was conducted off site, the reasons for this extreme variation in measurements are presently unknown. Both testing houses guarantee conformance to ASTM E1461. Whatever the case, those skilled in performing laser flash tests have not demonstrated that this technique, now used almost universally for thermal conductivity measurements, is appropriate for tungsten heavy alloy. To the contrary, conductivity measurements obtained to date suggest the flash diffusivity approach is unreliable for this material. The higher industry accepted values of 110-130 W/m-K were no doubt made by techniques that predated laser flash diffusivity and measured conductivity directly using larger size samples. No presently available source for repeating earlier test methods is known.

S. G. Caldwell
Technical Director – Tungsten Alloys

FIGURE AND TABLE NO. 58R. RECOMMENDED VALUES FOR THERMAL LINEAR EXPANSION OF TUNGSTEN W



RECOMMENDED VALUES

[Temperature, T, K; Linear Expansion, $\Delta L/L_0$, %; α, K^{-1}]

T	$\Delta L/L_0$	$\alpha \times 10^6$
5	-0.086	0.0006
25	-0.086	0.21
50	-0.085	0.88
100	-0.076	2.6
200	-0.040	4.1
293	0.000	4.5
400	0.048	4.5
500	0.093	4.6
600	0.140	4.7
700	0.188	4.8
800	0.237	5.0
900	0.287	5.0
1000	0.339	5.2
1200	0.444	5.3
1400	0.551	5.4
1600	0.661	5.6
1800	0.774	5.8
2000	0.893	6.1
2200	1.020	6.6
2400	1.157	7.1
2600	1.307	7.8
2800	1.469	8.3
3000	1.646	9.2
3200	1.837	10.0
3400	2.042	10.8
3600	2.263	11.6

REMARKS

The tabulated values are considered accurate to within ±3% over the entire temperature range. These values can be represented approximately by the following equations:

$$\Delta L/L_0 = 4.266 \times 10^{-4}(T - 293) + 8.479 \times 10^{-8}(T - 293)^2 - 1.974 \times 10^{-11}(T - 293)^3 \quad (293 < T < 1395)$$

$$\Delta L/L_0 = 0.548 + 5.416 \times 10^{-4}(T - 1395) + 1.952 \times 10^{-8}(T - 1395)^2 + 4.422 \times 10^{-11}(T - 1395)^3 \quad (1395 < T < 2495)$$

$$\Delta L/L_0 = 1.226 + 7.451 \times 10^{-4}(T - 2495) + 1.654 \times 10^{-7}(T - 2495)^2 + 7.568 \times 10^{-12}(T - 2495)^3 \quad (2495 < T < 3600)$$

Excerpt, *Formulas for Stress, Strain, and Structural Matrices*, by Walter D. Pilkey, 1st Ed. Table 4-1 (Partial), "Moduli of Elasticity, Poisson's Ratios, and Thermal Coefficients of Expansion," Page 176

TABLE 4-1 (continued) MODULI OF ELASTICITY, POISSON'S RATIOS, AND THERMAL COEFFICIENTS OF EXPANSION

Material	Modulus of Elasticity, E		Poisson's Ratio, ν	Thermal Coefficient of Expansion, α	
	$\times 10^6$ psi[a]	GPa		$\times 10^{-6}/°C$[b]	$\times 10^{-6}/°F$
Teflon—TFE	0.038–0.065	0.26–0.45	—	55	99
TiC	67	462	—	4	7.2
Titanium—6 Al-4V	16.5	115	0.34	4.9	8.8
Titanium—pure	15.1	104	0.34	4.8	8.6
Titanium—silicate	9.8	68	0.17	0.0 (±0.017)	0.0 (±0.03)
Tungsten	50	345	0.28	2.4–2.6	4.3–4.7
Tungsten-Carbide Cermet	61.6–94.3	425–650	—	2.5–3.0	4.5–5.4
Vanadium	18–20	124–138	—	4.6	8.3
Vinyl Chloride—rigid	0.3–0.5	2–3.5	0.28–0.34	28–56	50–100
Wood—structural	1–2	7–14	—	1–3	2–5
Zircaloy-2	11	76	0.37–0.41	2.9	5.2
Zirconium	13.7–14.0	95–96.5	0.37–0.41	3.1	5.6

[a] For psi, multiply tabulated values by 10^6. For example, if the entry is 40, this corresponds to 40×10^6 psi. An entry of 0.2–0.4 means that the values of E range from 0.2×10^6 psi to 0.4×10^6 psi.
[b] For α, multiply tabulated value by 10^{-6}. For example, for "Aluminum-Alloy 2024-T4", the α values are $12.9 \times 10^{-6}/°F$ and $23.2 \times 10^{-6}/°C$.
[c] E_1, ν_1 properties in fiber direction.
[d] E_2, ν_2 properties in 90° to fiber direction.

Firth Sterling
ATI Engineered Products

1297 County Line Road, Madison, AL 35756 256-464-7738 scaldwell@atimwp.com

4 September 2008

Troy Hedger / Raul J. Pomares
Alpha-Omega Services, Inc.
9156 Rose Street
Bellflower, CA 90706

Dear Troy / Raul:

I have prepared the following comments in response to your request to address the differences between our previously reported data (under Alpha-Omega Services P.O. #AOS-03590) and the cited specific heat values listed in NUREG/CR-6150.

In briefly revisiting previously submitted project reports, the initial thermal analysis data presented as part of our 7 September 2006 report contained a *Transmittal of Test Results* document from Anter Laboratories, a leading thermal analysis equipment manufacturer and provider of toll thermal analysis services. Testing of our tungsten heavy alloy grade SD180 material used in work defined by the referenced AOS purchase order was conducted by laser flash measurement, as described by ASTM E1461-01 using NIST traceable standards in a NADCAP certified laboratory. This testing house was extremely well qualified to make accurate measurements of specific heat.

Data were obtained at 5 temperatures of interest. The following values were reported by Anter for the 18.1 g/cc density tungsten heavy alloy (nominal composition 95W-3.57Ni-1.43Fe):

Nominal Temperature (F)	Specific Heat (J/[kg-K])
RT	154.7
200	159.2
400	163.4
600	170.3
800	173.9

Then, at a later date, additional thermal analysis of a SD180 sample was performed by Netzsch, who is also both a manufacturer of thermal analysis equipment as well as a toll service provider. As our 11 December 2006 report detailed, Netzsch obtained the following result using the same laser flash ASTM E1461 technique:

Nominal Temperature (F)	Specific Heat (J/[g-K])
RT	0.153

When the reported unit of measure is converted from a gram to kilogram basis, this supplemental testing by a second independent testing house yielded excellent agreement in specific heat – a value of 153 compared to the earlier 154.7 (J/[kg-K]). These values were thus in agreement within ~1.1% - an excellent match for single test data comparison.

In examining Section 15 of NUREG/CR-6150, it is not surprising to find disagreement in specific heat values to those we reported – it is rather to be expected. Tables 15-1 and 15-2 both list date for pure, elemental tungsten (W) – not tungsten heavy alloy. The SD180 alloy additionally contains Fe and Ni, and possesses a lower theoretical alloy density that pure W.

The relevance of previously reported specific heat values for the SD180 used in the aforementioned project over those contained in the cited NUREG document can therefore be summarized as follows:

1. NUREG/CR-6150 does not even relate to the tungsten heavy alloy used in the cask project.
2. NUREG/CR-6150 contains calculated values only, whereas our reported values were from actual material testing conducted by equipment manufacturers to an ASTM standard.
3. The thermodynamic data used for computation of NUREG/CR-6150 data are not given in Section 15. Even for the case of pure W, the calculated density reported in NUREG/CR-6150 Section 15.3 is 19.600 g/cc, which is greater than the tungsten industry accepted value of 19.3 g/cc for W as well as the value of 19.30 g/cc specified in the National Institute of Standards Physical Reference Data listing. It would appear that at least that input datum used in thermal calculations is in slight error even for the case of pure W. Calculated data are only as good as the input data and model.
4. Specific heat values we reported previously accounted for the actual measured density of the SD180 tungsten heavy alloy, as was determined using ASTM B311. As both chemical makeup and density varied from that of pure W, it is only natural that the thermal properties would differ from pure W as well.
5. The values we reported from Anter and Netzsch tests are consistent in trend with data for pure W in Table 15-1 of NUREG/CR-6150. For example, room temperature specific heat for pure W is listed as ~138 J/(kg-K), whereas testing of SD180 gave ~155 J/(kg-K) – an increase of ~12%. The tungsten heavy alloy contained 5 wt.% of transition metals having significantly higher specific heats than W (~460 J/(kg-K) for Ni, ~440 J/(kg-K) for Fe). It is therefore only expected that the room temperature specific heat for the SD180 heavy alloy would be higher than that of pure W.

There is therefore no reason whatsoever to question the specific heats reported by ATI Firth Sterling for SD180 based on NUREG/CR-6150. At best, the cited Section 15 data are not applicable for the reasons described above. Please contact me if further information is needed.

Yours truly,

Steven G. Caldwell

Steven G. Caldwell, Ph.D.
R&D Director
ATI Firth Sterling
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15. TUNGSTEN

15.1 Specific Heat (TUNGCP)

Specific heat is calculated by subroutine **TUNGCP** as a function of temperature. The temperature dependent specific heat[15-1] values are shown in Table 15-1. Linear interpolation is provided for temperature calls which fall between tabular values. Calls to **TUNGCP** that are outside of the table range will be returned with either the first or last table value.

Table 15-1. Specific heat of tungsten as a function of temperature.

Temperature (K)	Specific Heat (J/kg • K)
295	138.2
373	141.2
573	148.6
773	155.6
1,023	163.9
1,273	171.6
1,523	178.8
1,773	185.3
2,023	191.3
2,273	196.7
2,523	201.6
2,723	205.1
3,073	210.2

15.2 Thermal Conductivity (TUNGK)

Thermal conductivity is calculated by subroutine **TUNGK** as a function of temperature. The temperature dependent thermal conductivity[15-1] values are shown in Table 15-2. Linear interpolation is provided for temperature calls which fall between tabular values. Calls to **TUNGK** that are outside the table range will be returned with either the first or last table value.

Table 15-2. Thermal conductivity of tungsten as a function of temperature.

Temperature (K)	Thermal Conductivity (W/m • K)
573	124.7
673	122.9
773	121.2
873	119.4
1,073	161.1
1,773	114.5
1,373	111.5
1,573	108.6
2,573	96.73
2,973	93.16
3,173	91.63

15.3 Density Correlations (TUNGRO)

A constant value density[15-1] is returned by subroutine **TUNGRO**. The density value returned is 19600 (kg/m^3).

15.4 Reference

15-1 M. Firnhaber, K. Trambauer, S. Hagen, P. Hofmann, *Specification of the International Standard Problem ISP-31: CORA 13 Experiment on Severe Fuel Damage*, Gesellschaft für Reaktorsicherheit (GRS) mbH, August 1991.

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General Plastics LAST-A-FOAM

GENERAL PLASTICS MANUFACTURING CO.

DESIGN GUIDE FOR USE OF

LAST-A-FOAM® FR-3700

FOR

CRASH & FIRE PROTECTION

OF

RADIOACTIVE MATERIAL

SHIPPING CONTAINERS

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Product Data

LAST-A-FOAM® FR-3700 is a HCFC-free, rigid, closed-cell, flame-retardant polyurethane foam available in densities ranging from 4 to 40 pounds per cubic foot. It exhibits a high strength-to-weight ratio due to its cellular structure and crosslinked resin. Also, because of its closed-cell structure, LAST-A-FOAM® FR-3700 has great resistance to water absorption, and will not swell, crack, or split on exposure to water. LAST-A-FOAM® is stable, inert, and is resistant to most chemicals and solvents. It is easily worked with common tools, and performs well as a primary or replacement material in a variety of applications.

Basic Properties

Table 1: Basic Physical Properties

Property	English/Metric	Test Method
Closed Cell Content	96.7%	ASTM D-2856 Procedure B
Water Absorption	< 85% by weight	ASTM D-2842
Glass Transition	279°F / 137°C	MDSC
Hardness, Shore-D	1.7812(D) + 0.37	ASTM D-2240
Tumbling Friability - loss $^{w}/_{o}$	$41.314 \times 2.7183^{-0.1873(D)}$	ASTM C-421 (20 min. @ 60 rpm)

Table 2: Basic Chemical Properties

Property	English/Metric		Test Method
Chemical Composition	Carbon (C)	50-70%	--
	Oxygen (O)	14-34%	
	Nitrogen (N)	4-12%	
	Hydrogen (H)	4-10%	
	Phosphorous (P)	0-2%	
	Silicon (Si)	< 1%	
	Chloride (Cl)	< 1800 ppm	
	Other	< 1%	
Leachable Chlorides	< 1 ppm		GP-TM9510

Table 3: Thermal Properties

Property	English	Metric	Test Method
Thermal Conductivity	BTU/hr-ft^2-°F/inch	W/m-K	ASTM C177 @75°F (24°C)
FR-3704	0.200	0.029	
FR-3706	0.205	0.030	
FR-3708	0.209	0.030	
FR-3710	0.213	0.031	
FR-3718	0.324	0.047	
FR-3720	0.349	0.050	
FR-3725	0.414	0.060	
Specific Heat @25°C	0.353 BTU/lb-°F	1.477 J/g°C	ASTM E-1269
Heat of Combustion	11,706 BTU/lb	27.17 MJ/Kg	ASTM D-240
Coefficient of Linear Thermal Expansion From -50°F to 200°F	3.5×10^{-5} in/in/°F to 5.0×10^{-5} in/in/°F	6.2×10^{-5} K^{-1} to 9.0×10^{-5} K^{-1}	ASTM C-518

The Federal Aviation Regulation (FAR) 25.853(a) App. F(a)(1)(I) flame test is commonly used to asses the relative burning characteristics of foam plastic materials under controlled laboratory conditions. The results of these tests performed on LAST-A-FOAM® are shown in Table 4.

Table 4: Typical FAR 25.853 flame test results

LAST-A-FOAM® Grade	FAR 25.835 12-second Ignition		FAR 25.835 60-second Ignition	
	Extinguish Time, Seconds	Burn Distance, inches (mm)	Extinguish Time, Seconds	Burn Distance, inches (mm)
FR-3704	0.5	5.7 (144.8)	0.7	5.6 (142.2)
FR-3706	3.0	5.2 (132.0)	0.8	5.4 (137.2)
FR-3710	2.5	3.8 (96.5)	-0-	4.6 (116.8)
FR-3718	6.1	2.7 (68.6)	-0-	4.5 (114.3)
FR-3720	5.5	2.9 (73.7)	-0-	4.7 (119.4)

The results of these test are not to be considered or used as fire hazard classifications, and are not intended or implied to reflect hazards presented by this or any other material in actual fire conditions.

In the above tests, a 0.5 inch x 3.0 inch x 12 inch (12.7 mm x 76.2 mm x 305 mm) long foam sample is mounted in a vertical position. The lower end is exposed to a 1.5 inch (38.1 mm) Bunsen burner flame for the described time. The time to flame extinguishment after removal of the flame and burned length of the sample are recorded.

Chemical Resistance

LAST-A-FOAM® products exhibit very good-to-excellent resistance to a wide range of chemicals and solvents. Common petroleum products such as oil or gasoline have a negligible affect on LAST-A-FOAM®. Exposure to liquid acids and bases, either in dilute or highly-concentrated forms, does not significantly deteriorate foam properties at normal room temperatures. Some chlorinated solvents will cause LAST-A-FOAM® to temporarily swell or soften on exposure, which can be useful in some production situations. If you need specific advice regarding chemical resistance, please contact us.

Bonding, Filling, and Sealing LAST-A-FOAM

LAST-A-FOAM® can be bonded, filled sealed and painted with a wide variety of commercially available finishing products. Our customers report greatest success with automotive and wood finishing materials, but the range of usable products is not limited to those types.

General Plastics Manufacturing Company has prepare a "Guide to Bonding, Filling, and Sealing LAST-A-FOAM® Products", available on request, to help with making appropriate finishing material selections. You should follow manufacturer's safety instructions when using any bonding, filling, or finishing product with LAST-A-FOAM®, and observe their recommended precautions.

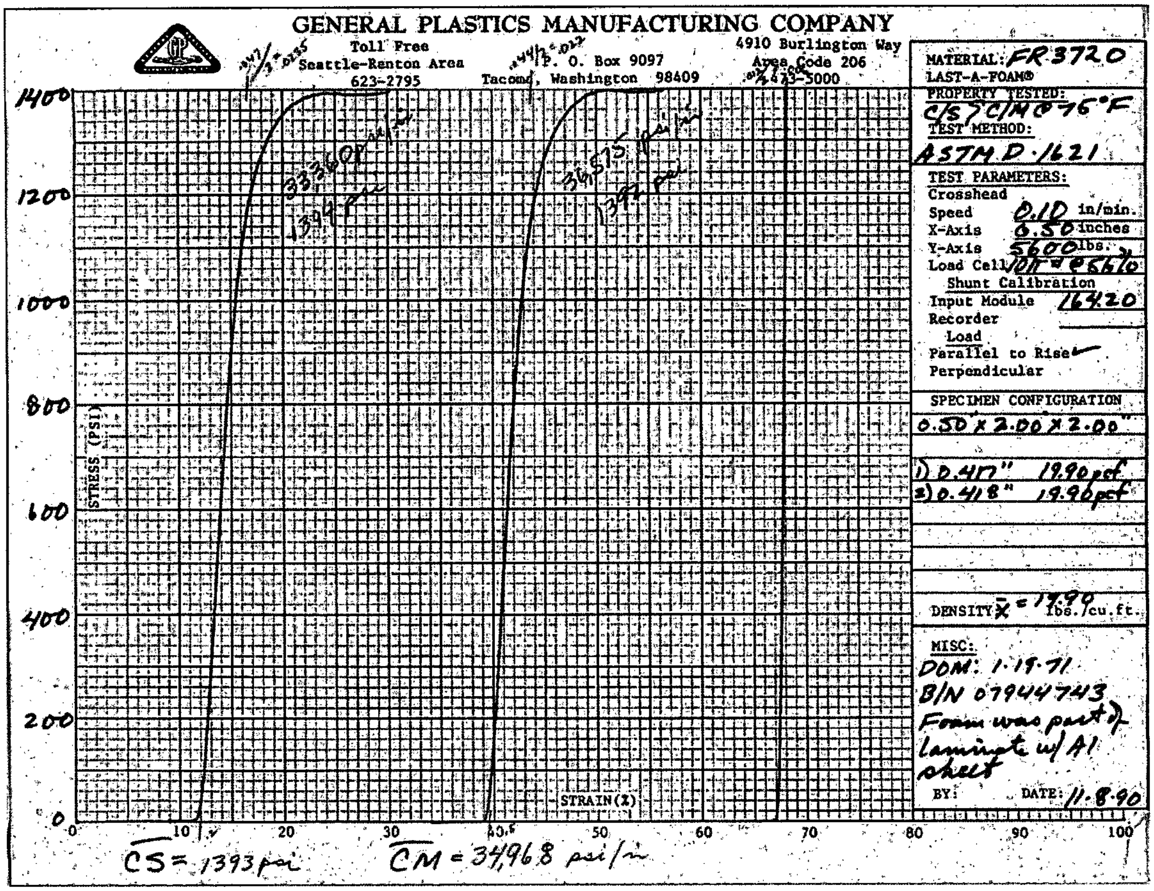

Figure 3: Long-Term Compressive Strength

Effect of Radiation

Cubic specimens (2.5 inch) LAST-A-FOAM® FR-3710 were submitted to the University of Michigan Phoenix Memorial Laboratory. The Specimens were irradiated in a Cobalt-60 Irradiator to a maximum cumulative dose of $2x10^8$ rads (gamma). This dosage is representative of approximately 40 years of life in a field of 500 rads per hour. Discoloration was observed to increase with dosage but was not correlated with any change of physical properties. The compressive strength of the specimens was unaffected by the radiation as evidenced by the data shown in Table 5 and Table 6. (Test date: 1994)

Table 5: Average of five specimens at each dosage (results for individual tests available upon request)

Exposure	DENSITY lbs/ft^3	Stress(psi) @ % Crush							
		10%	20%	30%	40%	50%	60%	65%	70%
Control	10.78	352	359	382	426	508	686	851	1,121
2 X 10^7 rads	10.68	341	348	373	417	499	678	848	1,137
4.2 X 10^7 rads	10.58	328	336	360	405	488	666	835	1,122
7 X 10^7 rads	10.64	333	341	366	408	491	666	831	1,106
2 X 10^8 rads	10.76	347	356	380	422	507	682	844	1,112

Water Immersion

Using the same cubic samples from the radiation testing, LAST-A-FOAM® FR-3710 was shown to remain resistant to significant water absorption. The samples were placed in water at temperature of 125°F (52°C) and a pressure of 17.7 psig (122 kPa). As shown by the results presented in Table 6, water absorption occurs slowly, even considering the affects of radiation exposure. Resistance to water absorption is consistent with the close cell content of LAST-A-FOAM® FR-3700 of greater than 95%.

Table 6: Water Absorption as a function of time and Radiation Exposure

Time and Radiation Exposure	Density, lbs/ft^3	Before Submersion	After Submersion	Weight Gain, grams	% Gain By Volume, *
1 Day Immersion					
Non Irradiated	10.61	44.19	47.29	3.10	1.21
2.0 X 10^7 rads	10.72	44.72	48.47	3.75	1.46
4.2 X 10^7 rads	10.96	45.66	48.88	3.22	1.26
7.0 X 10^7 rads	10.64	44.66	48.67	4.01	1.57
				Average-->	**1.37**
10 Day Immersion					
Non Irradiated	10.80	44.73	50.12	5.39	2.11
2.0 X 10^7 rads	10.61	44.51	51.93	7.42	2.90
4.2 X 10^7 rads	10.62	44.62	52.85	8.23	3.21
7.0 X 10^7 rads	10.65	44.29	53.78	9.49	3.71
				Average-->	**2.98**
100 Day Immersion					
Non Irradiated	10.87	45.35	61.74	16.39	6.40
2.0 X 10^7 rads	10.59	44.3	66.30	22.00	8.59
4.2 X 10^7 rads	10.89	45.35	67.70	22.35	8.73
7.0 X 10^7 rads	10.62	44.44	69.26	24.82	9.69
				Average-->	**8.35**
156 Day Immersion					
Non Irradiated	10.67	44.22	65.12	20.90	8.16
2.0 X 10^7 rads	10.52	43.89	69.70	25.81	10.08
4.2 X 10^7 rads	10.73	44.66	72.06	27.40	10.70
7.0 X 10^7 rads	10.73	44.58	74.59	30.01	11.72
				Average-->	**10.17**

Mechanical Properties

The data below are nominal values and appropriate tolerances should be considered when incorporating foam materials into static structural applications. Datasheet with values calculated may be found by following the link: LAST-A-FOAM® FR-3700 Datasheets.

CAUTION: When using metric units, you must convert the input variable, D (density), to English units (1 lb_m/ft^3 = 16.02 kg/m^3).

Property		Line of Best Fit Where 'D' is the foam density in lb_m/ft^3 (1 lb_m/ft^3 = 16.02 kg/m^3) English (psi)	Metric (MPa)	Test Method
Compressive Strength				
Parallel to Rise				
	@75°F	$= 8.745 (D)^{1.6154}$	$=0.0603 (D)^{1.6154}$	ASTM D-1621
	@250°F	$= 4.537 (D)^{1.6050}$	$=0.0313 (D)^{1.6154}$	
Perpendicular to Rise				
	@75°F	$= 3.456 (D)^{1.9178}$	$=0.0238 (D)^{1.6154}$	ASTM D-1621
	@250°F	$= 2.966 (D)^{1.7146}$	$=0.0205 (D)^{1.6154}$	
Compressive Modulus				
Parallel to Rise	@75°F	$= 276.2 (D)^{1.5413}$	$=1.9043 (D)^{1.6154}$	ASTM D-1621
	@250°F	$= 144.0 (D)^{1.6396}$	$=0.9928 (D)^{1.6154}$	
Perpendicular to Rise	@75°F	$= 74.66 (D)^{1.9995}$	$=0.5148 (D)^{1.6154}$	ASTM D-1621
	@250°F	$= 93.03 (D)^{1.7174}$	$=0.6414 (D)^{1.6154}$	
Tensile Strength				
Parallel to Rise		$= 29.68 (D)^{1.1496}$	$=0.2046 (D)^{1.6154}$	ASTM D-1623
Perpendicular to Rise		$= 14.74 (D)^{1.3852}$	$=0.1016 (D)^{1.6154}$	Type "A" Specimens
Tensile Modulus				
Parallel to Rise		$= 922.4 (D)^{1.1817}$	$=6.3597 (D)^{1.6154}$	ASTM D-1623
Perpendicular to Rise		$= 286.5 (D)^{1.5324}$	$=1.9753 (D)^{1.6154}$	Type "B" Specimens
Shear Strength				
Parallel to Rise		$= 7.530 (D)^{1.5433}$	$=0.0519 (D)^{1.6154}$	ASTM C-273
Perpendicular to Rise		$= 11.60 (D)^{1.3754}$	$=0.0800(D)^{1.6154}$	Compression Shear
Shear Modulus				
Parallel to Rise		$= 40.53 (D)^{1.8555}$	$=0.2794 (D)^{1.6154}$	ASTM C-273
Perpendicular to Rise		$= 133.0 (D)^{1.4209}$	$=0.9170 (D)^{1.6154}$	Compression Shear
Flexural Strength				
Parallel to Rise		$= 8.287 (D)^{1.6660}$	$=0.0571 (D)^{1.6154}$	ASTM D-790
Perpendicular to Rise		$= 21.17 (D)^{1.3614}$	$=0.1456 (D)^{1.6154}$	Method 1-A
Flexural Modulus				
Parallel to Rise		$= 151.2 (D)^{1.8084}$	$=1.0425 (D)^{1.6154}$	ASTM D-790
Perpendicular to Rise		$= 545.8 (D)^{1.3628}$	$=3.7631 (D)^{1.6154}$	Method 1-A

Table 7: Static Nominal Crush Strength, *Parallel* to Direction of Rise (see **Table 8** for *Perpendicular* to Rise)

For 4 to 10 lb_m/ft^3									
Temp	Correlation Factors	Crush Strength, psi, Parallel to Direction of Rise							
		10%	20%	30%	40%	50%	60%	65%	70%
-20°F	C_T	1.29	1.36	1.32	1.29	1.26	1.28	1.29	1.37
75°F	Y_{int}	**7.3058**	**6.7276**	**6.4961**	**6.9137**	**5.6711**	**5.3279**	**5.9871**	**6.2085**
	S	**1.6590**	**1.7021**	**1.7350**	**1.7255**	**1.8877**	**2.0431**	**2.0870**	**2.1868**
100°F	C_T	0.87	0.88	0.89	0.89	0.90	0.91	0.91	0.96
140°F	C_T	0.73	0.75	0.76	0.77	0.78	0.78	0.79	0.84
180°F	C_T	0.65	0.66	0.67	0.68	0.69	0.68	0.68	0.71
220°F	C_T	0.61	0.60	0.60	0.61	0.61	0.59	0.59	0.61
260°F	C_T	0.45	0.44	0.46	0.47	0.48	0.49	0.49	0.52
For 11 to 40 lb_m/ft^3									
Temp	Correlation Factor	Crush Strength, psi, Parallel to Direction of Rise							
		10%	20%	30%	40%	50%	60%	65%	70%
-20°F	C_T	1.35	1.33	1.32	1.31	1.31	1.30	1.28	1.26
75°F	Y_{int}	**4.3422**	**3.8755**	**3.5241**	**3.0307**	**3.0402**	**3.4889**	**5.8935**	**5.6055**
	S	**1.8809**	**1.9321**	**1.9872**	**2.0755**	**2.1451**	**2.2143**	**2.1041**	**2.2368**
100°F	C_T	0.86	0.87	0.88	0.88	0.89	0.90	0.90	0.97
140°F	C_T	0.72	0.74	0.75	0.75	0.75	0.76	0.76	0.81
180°F	C_T	0.62	0.63	0.65	0.65	0.65	0.65	0.64	0.68
220°F	C_T	0.56	0.56	0.57	0.57	0.56	0.54	0.54	0.57
260°F	C_T	0.40	0.40	0.41	0.42	0.41	0.43	0.43	0.47

The room temperature (75°F) foam crush strength is calculated at each %-Crush and is a function of density; $\sigma = Y_{int}(\rho)^S$, where Y_{int} and S are defined above, ρ is the nominal foam density in lb/ft^3, and σ in the resulting crush stress in psi at the indicated strain. The foam crush strength at temperatures other than 75°F is calculated at each %-Crush and is a function of the strength at 75°F; $\sigma = \sigma_{75^\circ F} C_T$. General Plastics Mfg. Co. is re-investigating the correlations factors at temperatures above and below 75°F. Please contact us for more specific and detailed data, as needed.

Table 8: Static Nominal Crush Strength, *Perpendicular* to Direction of Rise (see **Table 7** for *Parallel* to Rise)

For 4 to 10 lb_m/ft^3									
Temp	**Correlation Factors (see below)**	**Crush Strength, psi, Perpendicular to Direction of Rise**							
		10%	**20%**	**30%**	**40%**	**50%**	**60%**	**65%**	**70%**
-20°F	C_T	1.32	1.35	1.34	1.32	1.32	1.33	1.34	1.36
75°F	Y_{int}	**6.3841**	**6.5943**	**6.1154**	**5.7722**	**5.3041**	**5.3181**	**5.7864**	**5.7701**
	S	**1.7182**	**1.6946**	**1.7403**	**1.8023**	**1.9054**	**2.0392**	**2.1002**	**2.2255**
100°F	C_T	0.85	0.87	0.88	0.89	0.90	0.91	0.91	0.92
140°F	C_T	0.75	0.77	0.78	0.79	0.79	0.79	0.79	0.80
180°F	C_T	0.63	0.66	0.68	0.69	0.69	0.70	0.69	0.70
220°F	C_T	0.59	0.59	0.60	0.61	0.60	0.60	0.59	0.60
260°F	C_T	0.45	0.45	0.47	0.48	0.48	0.48	0.48	0.48
For 11 to 40 lb_m/ft^3									
Temp	**Correlation Factors (see below)**	**Crush Strength, psi, Perpendicular to Direction of Rise**							
		10%	**20%**	**30%**	**40%**	**50%**	**60%**	**65%**	**70%**
-20°F	C_T	1.34	1.33	1.32	1.33	1.30	1.28	1.24	1.17
75°F	Y_{int}	**4.1342**	**3.5581**	**3.2664**	**2.8352**	**2.8988**	**3.3972**	**6.5439**	**5.6464**
	S	**1.8957**	**1.9593**	**2.0109**	**2.0955**	**2.1602**	**2.2242**	**2.0660**	**2.2321**
100°F	C_T	0.84	0.85	0.86	0.88	0.87	0.88	0.88	0.90
140°F	C_T	0.72	0.73	0.74	0.76	0.75	0.76	0.76	0.79
180°F	C_T	0.62	0.63	0.64	0.65	0.65	0.65	0.65	0.67
220°F	C_T	0.53	0.53	0.54	0.55	0.54	0.54	0.54	0.56
260°F	C_T	0.39	0.39	0.40	0.41	0.41	0.40	0.40	0.42

The room temperature (75°F) foam crush strength is calculated at each %-Crush and is a function of density; $\sigma = Y_{int}(\rho)^S$, where Y_{int} and S are defined above, ρ is the nominal foam density in lb/ft^3, and σ in the resulting crush stress in psi at the indicated strain. The foam crush strength at temperatures other than 75°F is calculated at each %-Crush and is a function of the strength at 75°F; $\sigma = \sigma_{75^\circ F} C_T$. General Plastics Mfg. Co. is re-investigating the correlations factors at temperatures above and below 75°F. Please contact us for more specific and detailed data, as needed.

Dynamic Crush Strength

The crush strength of LAST-A-FOAM®, like many materials, is modestly sensitive to strain rate. The static to dynamic adjustment shown in Table 9 is based on a significant testing program and included strain rates in the range of 30 sec^{-1} to 100 sec^{-1}. It is expected that the adjustment will provide good predictions of dynamic impact strength of FR-3700 for most Packaging design conditions. This information is intended to be a guide for designers of impact mitigating devices. The constitutive material models may be useful in targeting a foam density or rage for a particular application. However, each design should be thoroughly analyzed or tested to understand the implications of the complete design.

Table 9: Static to Dynamic Crush Strength Adjustment

Strain	10%	20%	30%	40%	50%	60%	65%	70%
Y_{int}	1.2971	1.4397	1.5181	1.3887	1.4419	1.4275	1.3871	1.4660
S	1.0330	1.0069	0.9941	1.0028	0.9912	0.9831	0.9910	0.9586

The dynamic crush strength is calculated at each %-strain and a function of the static crush strength at the same %-strain;

$$\sigma_{Dynamic} = y_{int}(\sigma_{Static})^{S}.$$

CAUTION: Use only units of PSI for input σ_{Static} value.

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See our World Wide Wed Site at:
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E-mail address: sales@generalplastics.com

Air Properties

Air Properties

Properties from Incropera, Frank P., David P. DeWitt, *Fundamentals of Heat and Mass Transfer*, New York: John Wiley & Sons, Incorporated, 4th Ed., 1996.

Used modeling air gaps. Illustrations that follow show the Air gap locations (excerpt from Revision A of this report) and size of gap within the cask (dimensions included, Model AOS-165 provided as an example).

$$Gr = \frac{gS^3}{T\mu^2} \Delta T$$

← This part is calculated for different temperatures.

Results shows for large range of ΔT,

$Gr < 2000 \quad \therefore N_u = 1$

$\therefore h_c = k/s \quad k_c = h_c S$

Radiation assuming T1 ~ T2 (temperature across gap)

$h_r = J * F * 4T^3$

$F = 0.351$ (refer to Paragraph 3.3.1.2, "Enclosed Air Space Property Sets," within this report)

$K_R = h_r S$

Excerpt, *Fundamentals of Heat and Mass Transfer*, Table a.4, "Thermophysical Properties of Gases at Atmospheric Pressure," Page 839

TABLE A.4 Thermophysical Properties of Gases at Atmospheric Pressure[a]

T (K)	ρ (kg/m^3)	c_p (kJ/kg · K)	$\mu \cdot 10^7$ (N · s/m^2)	$\nu \cdot 10^6$ (m^2/s)	$k \cdot 10^3$ (W/m · K)	$\alpha \cdot 10^6$ (m^2/s)	Pr
Air							
100	3.5562	1.032	71.1	2.00	9.34	2.54	0.786
150	2.3364	1.012	103.4	4.426	13.8	5.84	0.758
200	1.7458	1.007	132.5	7.590	18.1	10.3	0.737
250	1.3947	1.006	159.6	11.44	22.3	15.9	0.720
300	1.1614	1.007	184.6	15.89	26.3	22.5	0.707
350	0.9950	1.009	208.2	20.92	30.0	29.9	0.700
400	0.8711	1.014	230.1	26.41	33.8	38.3	0.690
450	0.7740	1.021	250.7	32.39	37.3	47.2	0.686
500	0.6964	1.030	270.1	38.79	40.7	56.7	0.684
550	0.6329	1.040	288.4	45.57	43.9	66.7	0.683
600	0.5804	1.051	305.8	52.69	46.9	76.9	0.685
650	0.5356	1.063	322.5	60.21	49.7	87.3	0.690
700	0.4975	1.075	338.8	68.10	52.4	98.0	0.695
750	0.4643	1.087	354.6	76.37	54.9	109	0.702
800	0.4354	1.099	369.8	84.93	57.3	120	0.709
850	0.4097	1.110	384.3	93.80	59.6	131	0.716
900	0.3868	1.121	398.1	102.9	62.0	143	0.720
950	0.3666	1.131	411.3	112.2	64.3	155	0.723
1000	0.3482	1.141	424.4	121.9	66.7	168	0.726
1100	0.3166	1.159	449.0	141.8	71.5	195	0.728
1200	0.2902	1.175	473.0	162.9	76.3	224	0.728
1300	0.2679	1.189	496.0	185.1	82	238	0.719
1400	0.2488	1.207	530	213	91	303	0.703
1500	0.2322	1.230	557	240	100	350	0.685
1600	0.2177	1.248	584	268	106	390	0.688
1700	0.2049	1.267	611	298	113	435	0.685
1800	0.1935	1.286	637	329	120	482	0.683
1900	0.1833	1.307	663	362	128	534	0.677
2000	0.1741	1.337	689	396	137	589	0.672
2100	0.1658	1.372	715	431	147	646	0.667
2200	0.1582	1.417	740	468	160	714	0.655
2300	0.1513	1.478	766	506	175	783	0.647
2400	0.1448	1.558	792	547	196	869	0.630
2500	0.1389	1.665	818	589	222	960	0.613
3000	0.1135	2.726	955	841	486	1570	0.536
Ammonia (NH_3)							
300	0.6894	2.158	101.5	14.7	24.7	16.6	0.887
320	0.6448	2.170	109	16.9	27.2	19.4	0.870
340	0.6059	2.192	116.5	19.2	29.3	22.1	0.872
360	0.5716	2.221	124	21.7	31.6	24.9	0.872
380	0.5410	2.254	131	24.2	34.0	27.9	0.869

The decay heat of the cask contents is introduced in the model by two-node convective boundary elements along the cask cavity wall. In the model, it is assumed that the load is uniformly distributed over the entire cavity surface.

Convective boundary elements define the convective and radiative properties at the interface between the impact limiter outer surface and the regulatory environments. Another convective surface is located on the side of the cask's outer shell, between the upper and lower impact limiter structures. In addition to convective and radiative properties, these boundary two-node elements have the capability to include required solar heat flux loads.

Figure 3-2 illustrates all components and interfaces of the thermal model.

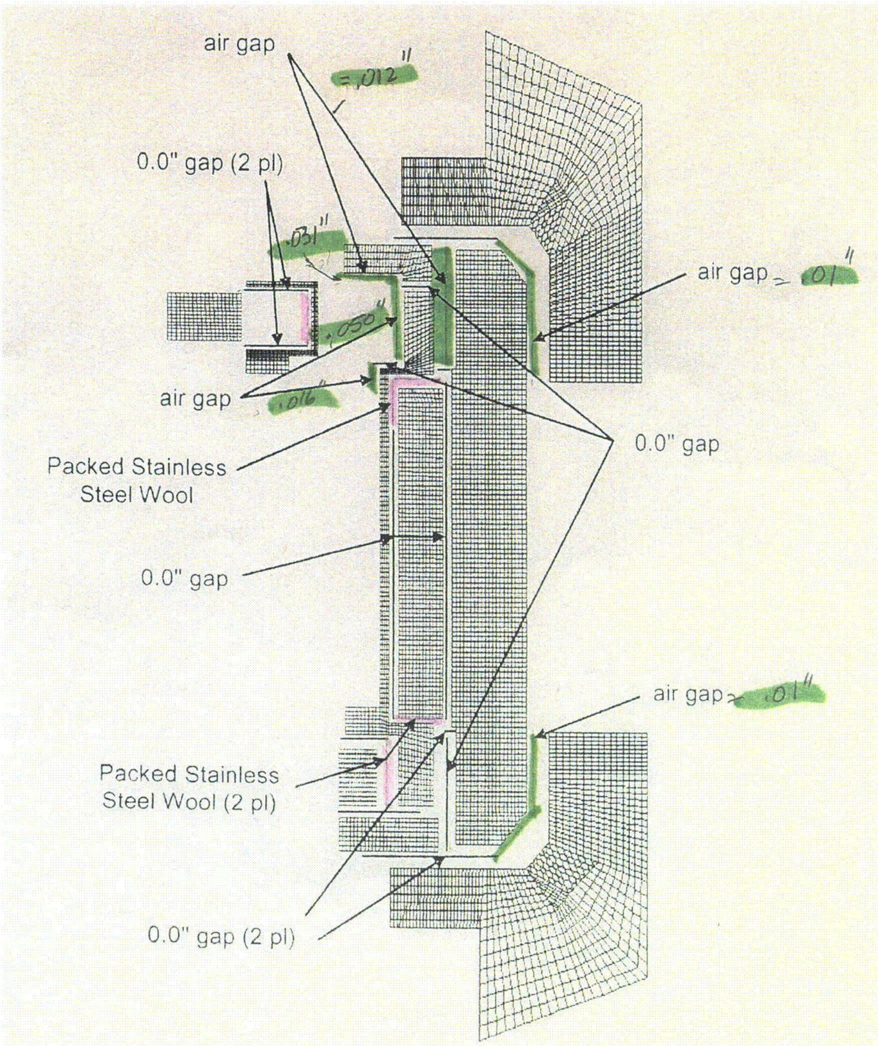
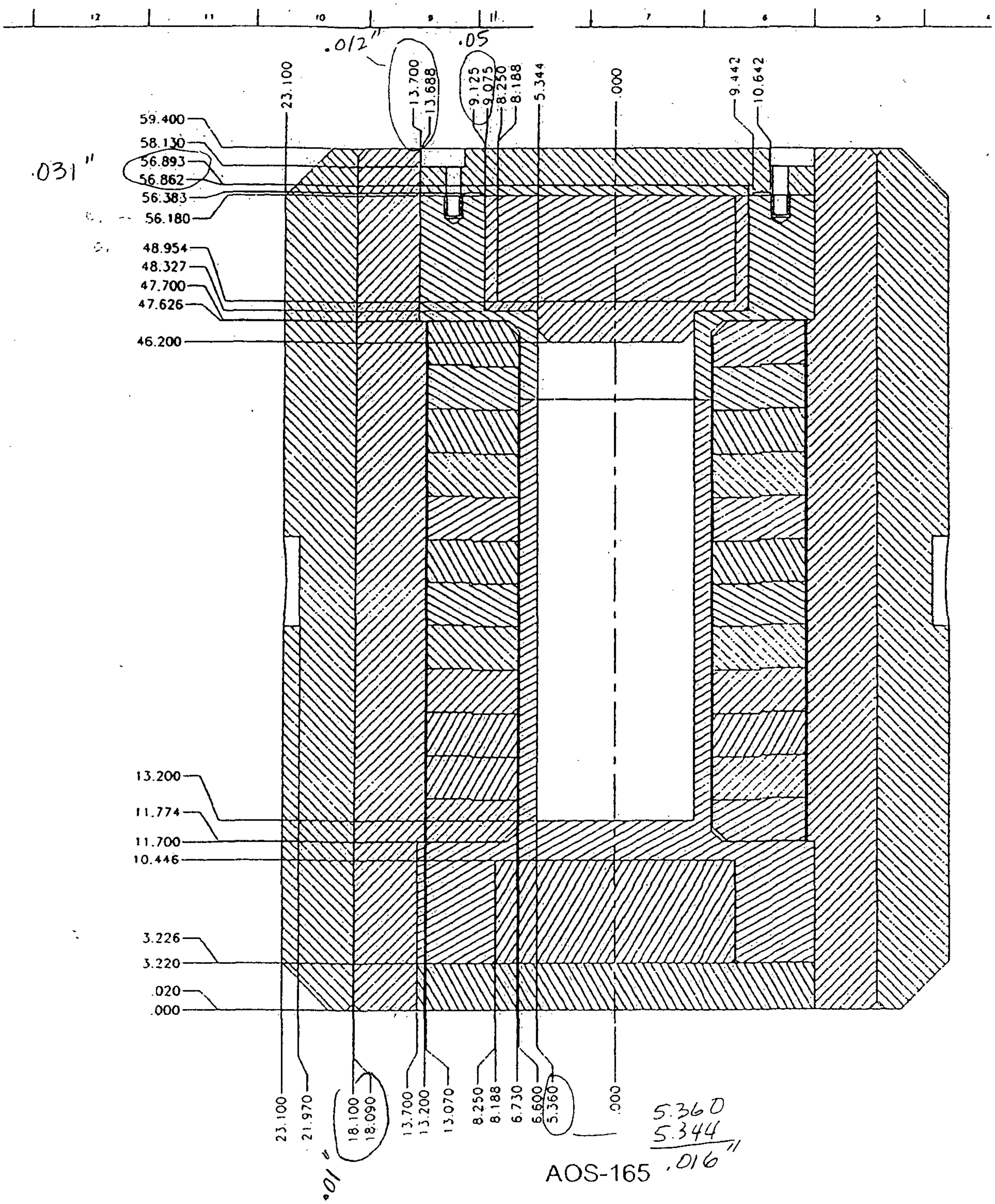


Figure 3-2. Expanded View of Thermal Model Defining Component Interfaces

Size of Gap within Cask – Model AOS-165



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Port Seal

Parker

Compound Data Sheet
Parker O-Ring Division United States

MATERIAL REPORT

REPORT NUMBER: KK2206
DATE: 06/19/96

TITLE: Evaluation of Parker Compound S1224-70 to ASTM D2000 7GE705 A19 B37 EA14 EO16 E036 F19 G11

PURPOSE: To determine if S1224-70 meets the callout.

CONCLUSION: Compound S1224-70 meets the ASTM D2000 callout.

Recommended temperature limits: -65^{0}F to 450^{0}F

Recommended For
Dry heat
Some petroleum oils
Moderate water resistance
Fire resistant hydraulic fluids (HFD-R and HFD-S)
Ozone, aging, and weather resistance
Low temperature

Not Recommended For
Ketones
Acids
Silicone oils
Auto and aircraft brake fluid

Parker O-Ring Division
2360 Palumbo Drive
Lexington, Kentucky 40509
(859) 269-2351

Compound Data Sheet
Parker O-Ring Division United States

REPORT DATA

Report Number:	KK2206

	ASTM D2000 **7GE705 A19 B37 EA14 EO16 E036 F19 G11** Pass / Fail Limits	**S1224-70** Slab Results
Basic Physical Properties		
Hardness	70 +/- 5	69
Tensile Strength, psi min	725	1204
Elongation, % min	150	265
ASTM D573 Heat Aging, 70 HRS @ 225^{0}C		
Hardness Change, pts max	+10	+6
Tensile Change, % max	-25	-14
Elongation Change, % max	-30	-26
Compression Set ASTM D395, 22 HRS @ 347^{0}F, plies		
% of Original Deflection, max	30	23
Fluid Immersion, ASTM #1 Oil, 70 HRS @ 150^{0}C		
Hardness Change, pts	0 to -15	-9
Tensile Change, % max	-20	+10
Elongation Change, % max	-20	+3
Volume Change, %	0 to +15	+4
Fluid Immersion, ASTM #3 Oil, 70 HRS @ 302^{0}F		
Hardness Change, pts max	-40	-19
Volume Change, % max	+60	+35
Fluid Immersion ASTM D471 Water 70 HRS. @ 212^{0}F		
Hardness Change, pts. max.	+/-5	0
Volume Change, % max.	+/-5	0
Tear Resistance, ASTM D624, Die B		
kN/M, min	9	14
Low Temperature BrittlenessTest ASTM D2137, Method A		
3 min. @ -55^{0}C	Pass	Pass

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Lid Seal

Dimensions in inches

Jacket Material	HELIUM SEALING							BUBBLE SEALING				
	Cross Section	e_2	e_C	Y_2 lbs/inch	Y_1 lbs/inch	Pu68°F PSI	PuΘ392°F PSI	Y_2 lbs/inch	Y_1 lbs/inch	Pu68°F PSI	PuΘ392°F PSI	Max Temp °F
Aluminum	0.063	0.024	0.028	857	114	7250	N/A	514	114	5075	N/A	302
	0.075	0.028	0.033	914	114	7540	N/A	571	114	5800	N/A	302
	0.087	0.028	0.035	942	114	7685	N/A	600	114	5800	N/A	356
	0.098	0.028	0.035	999	114	7975	725	657	114	6090	725	428
	0.118	0.031	0.039	1056	143	7975	1450	742	114	6525	1450	482
	0.138	0.031	0.039	1085	143	7975	2030	799	114	6815	2030	482
	0.157	0.035	0.043	1142	143	8700	2465	857	114	7250	2465	536
	0.177	0.035	0.047	1199	143	8700	2900	914	114	7540	2900	536
	0.197	0.035	0.055	1256	171	9135	3190	971	143	7975	3190	572
	0.217	0.035	0.063	1313	171	9425	3480	1028	143	8265	3480	608
	0.236	0.039	0.071	1399	200	9715	3625	1113	171	8700	3625	644
	0.276	0.039	0.087	1542	228	10150	4060	1171	200	9425	4060	644
	0.315	0.039	0.102	1656	286	10440	4640	1285	228	9860	4495	680
							PuΘ482°F				PuΘ482°F	
Silver	0.063	0.020	0.024	1142	171	9425	N/A	857	171	5800	N/A	464
	0.075	0.024	0.028	1256	171	9425	N/A	857	171	5800	N/A	464
	0.087	0.024	0.031	1313	200	10150	N/A	914	171	5800	580	536
	0.098	0.028	0.035	1370	257	10875	1160	971	228	6525	725	536
	0.118	0.031	0.039	1485	286	12325	2030	1028	257	7250	1305	572
	0.138	0.031	0.039	1599	286	13775	3190	1085	257	7975	1885	572
	0.157	0.031	0.043	1713	314	15225	3915	1142	286	8700	2320	662
	0.177	0.031	0.043	1827	343	16675	4495	1256	286	10150	2755	698
	0.197	0.031	0.051	1941	343	18125	5220	1313	286	11600	3190	698
	0.217	0.031	0.055	2056	371	19575	5800	1428	343	13050	3625	752
	0.236	0.035	0.067	2284	400	21750	6815	1542	343	15950	4350	842
	0.276	0.035	0.079	2512	457	23200	7830	1713	371	18125	5220	842
	0.315	0.035	0.094	2798	514	24650	8700	1999	400	20300	6090	932
							PuΘ572°F				PuΘ572°F	
Copper, Soft Iron, Mild Steels and Annealed Nickel	0.063	0.020	0.024	1485	228	7250	1450	1085	171	5075	725	662
	0.075	0.024	0.028	1599	286	7250	1595	1142	228	5075	870	662
	0.087	0.024	0.031	1713	343	7975	1885	1256	286	5075	1160	680
	0.098	0.028	0.035	1827	400	8700	2465	1313	343	5800	1450	716
	0.118	0.028	0.039	1999	457	9425	2900	1428	400	5800	1740	716
	0.138	0.028	0.039	2227	457	10150	3335	1542	400	6525	2175	752
	0.157	0.031	0.043	2455	514	10150	3915	1656	457	6525	2465	788
	0.177	0.031	0.043	2684	571	11600	4350	1827	457	6525	2755	842
	0.197	0.031	0.051	2912	628	12325	4785	1884	514	7250	3045	842
	0.217	0.031	0.055	3141	685	13050	5220	2056	571	7250	3335	896
	0.236	0.035	0.067	3597	799	13775	5800	2284	571	7975	3770	968
	0.276	0.035	0.079	4225	914	14500	6525	2627	628	8700	4205	968
	0.315	0.035	0.094	4911	1085	15950	7105	3026	742	9425	4640	1022
							PuΘ662°F				PuΘ662°F	
Nickel, Monel, Tantalum	0.063	0.016	0.020	1827	457	10150	1595	1142	343	5800	1015	716
	0.075	0.020	0.024	1999	457	10440	2320	1256	343	6090	1305	716
	0.087	0.020	0.028	2227	514	11020	3045	1313	400	6380	1740	788
	0.098	0.024	0.031	2512	571	11890	3915	1542	400	6815	2320	842
	0.118	0.024	0.035	2512	628	12615	4930	1713	457	7250	2900	896
	0.138	0.024	0.035	2798	685	13485	5800	1941	514	7830	3335	932
	0.157	0.028	0.039	3312	799	13920	6525	2170	571	8265	3915	1022
	0.177	0.028	0.039	4111	857	15225	7540	2398	628	8700	4350	1112
	0.197	0.028	0.043	4454	1028	15950	8265	2627	628	9425	4785	1202
	0.217	0.028	0.051	4625	1142	16675	8990	2855	685	9715	5365	1202
	0.236	0.031	0.063	N/A	N/A	N/A	N/A	3198	742	10440	5945	1202
	0.276	0.031	0.071	N/A	N/A	N/A	N/A	3712	857	11310	6525	1202
	0.315	0.031	0.083	N/A	N/A	N/A	N/A	4168	914	12035	7250	1202
							PuΘ752°F				PuΘ752°F	
Stainless Steel, Inconel, Titanium	0.063	0.016	0.020	1999	571	13050	3625	1713	457	6815	870	788
	0.075	0.020	0.024	2284	571	13195	3915	1827	457	7250	1160	788
	0.087	0.020	0.028	2570	628	13340	4205	1999	514	7540	1595	896
	0.098	0.024	0.031	2855	685	14065	4640	2170	571	8265	2175	932
	0.118	0.024	0.035	3283	742	14500	5220	2427	628	8990	2900	932
	0.138	0.024	0.035	3769	857	15080	5655	2684	742	9715	3625	1022
	0.157	0.028	0.039	4283	971	15515	6090	2969	857	10440	4350	1112
	0.177	0.028	0.039	4711	1256	15950	6525	3198	1028	11165	4930	1202
	0.197	0.028	0.043	N/A	N/A	N/A	N/A	3426	1085	11890	5365	1292
	0.217	0.028	0.051	N/A	N/A	N/A	N/A	3712	1142	12615	6090	1292
	0.236	0.031	0.063	N/A	N/A	N/A	N/A	4111	1256	13630	6815	1292
	0.276	0.031	0.071	N/A	N/A	N/A	N/A	4568	1485	14790	7540	1292
	0.315	0.031	0.083	N/A	N/A	N/A	N/A	5139	1656	15660	8410	1292

HELICOFLEX®

Spring Energized Seals

SEAL AND GROOVE DIMENSIONS

Dimensions in inches

	SEAL			GROOVE				
				Pressure < 300psi	Pressure ≥ 300psi			
Jacket Material	Free Height	Installation Compression e2	Seal Diameter Range	Diametrical Clearance X	Diametrical Clearance X	Groove Depth F	Groove Width (Min.) G	Groove Finish RMS
Aluminum	0.063	0.024	0.500 to 4.000	0.024	0.012	0.039 +/- 0.003	0.111	32-125 Contact Applications Engineering for Recommendation
	0.075	0.028	0.625 to 6.000	0.028	0.012	0.047 +/- 0.003	0.131	
	0.087	0.028	0.750 to 10.000	0.028	0.012	0.059 +/- 0.003	0.143	
	0.098	0.028	0.875 to 15.000	0.028	0.012	0.070 +/- 0.003	0.154	
	0.118	0.031	1.000 to 20.000	0.031	0.012	0.087 +/- 0.004	0.180	
	0.138	0.031	1.250 to 25.000	0.031	0.020	0.107 +/- 0.004	0.200	
	0.157	0.035	1.750 to 30.000	0.035	0.020	0.122 +/- 0.004	0.227	
	0.177	0.035	2.000 to 40.000	0.035	0.020	0.142 +/- 0.004	0.247	
	0.197	0.035	3.000 to 50.000	0.035	0.020	0.162 +/- 0.004	0.267	
	0.217	0.035	4.000 to 50.000 +	0.035	0.020	0.182 +/- 0.004	0.287	
	0.236	0.039	5.000 to 50.000 +	0.039	0.020	0.197 +/- 0.005	0.314	
	0.276	0.039	6.000 to 50.000 +	0.039	0.028	0.237 +/- 0.005	0.354	
	0.315	0.039	8.000 to 50.000 +	0.039	0.028	0.276 +/- 0.005	0.393	
Silver	0.063	0.020	0.500 to 4.000	0.020	0.012	0.043 +/- 0.002	0.103	63-125 Contact Applications Engineering for Recommendation
	0.075	0.024	0.625 to 6.000	0.024	0.012	0.051 +/- 0.003	0.123	
	0.087	0.024	0.750 to 10.000	0.024	0.012	0.063 +/- 0.003	0.135	
	0.098	0.028	0.875 to 15.000	0.028	0.012	0.070 +/- 0.003	0.154	
	0.118	0.031	1.000 to 20.000	0.031	0.012	0.087 +/- 0.004	0.180	
	0.138	0.031	1.250 to 25.000	0.031	0.020	0.107 +/- 0.004	0.200	
	0.157	0.031	1.750 to 30.000	0.031	0.020	0.126 +/- 0.004	0.219	
	0.177	0.031	2.000 to 40.000	0.031	0.020	0.146 +/- 0.004	0.239	
	0.197	0.031	3.000 to 50.000	0.031	0.020	0.166 +/- 0.004	0.259	
	0.217	0.031	4.000 to 50.000 +	0.031	0.020	0.186 +/- 0.004	0.279	
	0.236	0.035	5.000 to 50.000 +	0.035	0.020	0.201 +/- 0.004	0.306	
	0.276	0.035	6.000 to 50.000 +	0.035	0.028	0.241 +/- 0.004	0.346	
	0.315	0.035	8.000 to 50.000 +	0.035	0.028	0.280 +/- 0.004	0.385	
Copper, Soft Iron, Mild Steels and Annealed Nickel	0.063	0.020	0.500 to 4.000	0.020	0.012	0.043 +/- 0.002	0.103	63-125 Contact Applications Engineering for Recommendation
	0.075	0.024	0.625 to 6.000	0.024	0.012	0.051 +/- 0.003	0.123	
	0.087	0.024	0.750 to 10.000	0.024	0.012	0.063 +/- 0.003	0.135	
	0.098	0.028	0.875 to 15.000	0.028	0.012	0.070 +/- 0.003	0.154	
	0.118	0.028	1.000 to 20.000	0.028	0.012	0.090 +/- 0.003	0.174	
	0.138	0.028	1.250 to 25.000	0.028	0.020	0.110 +/- 0.003	0.194	
	0.157	0.031	1.750 to 30.000	0.031	0.020	0.126 +/- 0.004	0.219	
	0.177	0.031	2.000 to 40.000	0.031	0.020	0.146 +/- 0.004	0.239	
	0.197	0.031	3.000 to 50.000	0.031	0.020	0.166 +/- 0.004	0.259	
	0.217	0.031	4.000 to 50.000 +	0.031	0.020	0.186 +/- 0.004	0.279	
	0.236	0.035	5.000 to 50.000 +	0.035	0.020	0.201 +/- 0.004	0.306	
	0.276	0.035	6.000 to 50.000 +	0.035	0.028	0.241 +/- 0.004	0.346	
	0.315	0.035	8.000 to 50.000 +	0.035	0.028	0.280 +/- 0.004	0.385	
Nickel, Monel, Tantalum	0.063	0.016	0.500 to 4.000	0.016	0.012	0.047 +/- 0.002	0.095	32-63 Contact Applications Engineering for Recommendation
	0.075	0.020	0.625 to 6.000	0.020	0.012	0.055 +/- 0.002	0.115	
	0.087	0.020	0.750 to 10.000	0.020	0.012	0.067 +/- 0.002	0.127	
	0.098	0.024	0.875 to 15.000	0.024	0.012	0.074 +/- 0.003	0.146	
	0.118	0.024	1.000 to 20.000	0.024	0.012	0.094 +/- 0.003	0.166	
	0.138	0.024	1.250 to 25.000	0.024	0.020	0.114 +/- 0.003	0.186	
	0.157	0.028	1.750 to 30.000	0.028	0.020	0.129 +/- 0.003	0.213	
	0.177	0.028	2.000 to 40.000	0.028	0.020	0.149 +/- 0.003	0.233	
	0.197	0.028	3.000 to 50.000	0.028	0.020	0.169 +/- 0.003	0.253	
	0.217	0.028	4.000 to 50.000 +	0.028	0.020	0.189 +/- 0.003	0.273	
	0.236	0.031	5.000 to 50.000 +	0.031	0.020	0.205 +/- 0.004	0.298	
	0.276	0.031	6.000 to 50.000 +	0.031	0.028	0.245 +/- 0.004	0.338	
	0.315	0.031	8.000 to 50.000 +	0.031	0.028	0.284 +/- 0.004	0.377	
Stainless Steel, Inconel, Titanium	0.063	0.016	0.500 to 4.000	0.016	0.012	0.047 +/- 0.002	0.095	32-63 Contact Applications Engineering for Recommendation
	0.075	0.020	0.625 to 6.000	0.020	0.012	0.055 +/- 0.002	0.115	
	0.087	0.020	0.750 to 10.000	0.020	0.012	0.067 +/- 0.002	0.127	
	0.098	0.024	0.875 to 15.000	0.024	0.012	0.074 +/- 0.003	0.146	
	0.118	0.024	1.000 to 20.000	0.024	0.012	0.094 +/- 0.003	0.166	
	0.138	0.024	1.250 to 25.000	0.024	0.020	0.114 +/- 0.003	0.186	
	0.157	0.028	1.750 to 30.000	0.028	0.020	0.129 +/- 0.003	0.213	
	0.177	0.028	2.000 to 40.000	0.028	0.020	0.149 +/- 0.003	0.233	
	0.197	0.028	3.000 to 50.000	0.028	0.020	0.169 +/- 0.003	0.253	
	0.217	0.028	4.000 to 50.000 +	0.028	0.020	0.189 +/- 0.003	0.273	
	0.236	0.031	5.000 to 50.000 +	0.031	0.020	0.205 +/- 0.004	0.298	
	0.276	0.031	6.000 to 50.000 +	0.031	0.028	0.245 +/- 0.004	0.338	
	0.315	0.031	8.000 to 50.000 +	0.031	0.028	0.284 +/- 0.004	0.377	

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3.5.8 Data CDs

All thermal input/output files, as well as all Autodesk Inventor files, are attached on the Compact Discs (CDs), as listed below:

- **CDs 1, 2, and 3** – All analytical files, including the LIBRA FE program
- **CD 4** – Autodesk Inventor files

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3.5.9 Justification for Use of Uniformly Distributed Decay Heat throughout Cask Cavity

Typically, the content is placed in the cask cavity in a basket or rack device. This device provides shoring to the content, to ensure that its loading arrangement is maintained during transportation. Selection of the type of material for fabrication of this device is based upon the temperature environment within the cask cavity. A cavity temperature of less than 400°F will allow the use of aluminum. For temperatures of 400°F or greater, the choice is stainless steel material, although this material could be used in either case.

The cavity temperature within all AOS Transport System Models is less than 300°F under Normal conditions of transport; therefore, the use of either material in the fabrication of the shoring devices is acceptable.

In the AOS cask analyses, the decay heat is assumed to be uniformly distributed throughout the cask cavity. The effect of this assumption is examined here, by comparing cask stress and temperatures corresponding to three assumed distributions of decay heat over the surface of the cask cavity. The three assumed distributions represent usual, assumed decay heat distributions over the cask cavity cylinder, top, and bottom.

- **Case 1** – Decay heat uniformly distributed over the cask cavity cylindrical surface, top surface, and bottom surface (as in the AOS analyses).
- **Case 2** – Decay heat distributed over the cask cavity cylindrical surface, top surface, and bottom surface, such that the cylindrical surface receives twice the heat intensity as the top and bottom surfaces.
- **Case 3** – Decay heat distributed over only cask cavity cylindrical surface, with the top and bottom surfaces receiving no heat.

Cask temperatures and thermal stress were determined for each of the three distributions. The maximum component temperatures are presented in Table 3-100 through Table 3-102, and cask temperature distributions are illustrated in Figure 3-146 through Figure 3-148. Pm and Pb stress at the critical cask cross-sections are presented in Table 3-103 through Table 3-105, and plots of maximum principal stress in the cask dog-leg region are illustrated in Figure 3-149 through Figure 3-151.

A comparison of Table 3-100 through Table 3-102 shows little variation in maximum temperature for the three heat distributions. Figure 3-146 through Figure 3-148 show that Case 1, uniformly distributed decay heat, provides maximum temperature in the seal region. From Table 3-100 through Table 3-102, the maximum temperature difference is less than 6°F.

A comparison of Table 3-103 through Table 3-105 shows little variation in stress due to heat distribution. Maximum thermal bending stress occurs at Location 4, and the maximum stress difference due to heat distribution is 0.5 ksi. Figure 3-149 through Figure 3-151 also show only a small stress difference in the cask dog-leg region due to the heat distribution.

In the AOS cask analyses, thermal stress due to maximum decay heat represents only a small portion of total stress in all load combinations. As a result, the small stress change in the three cases shows that a change in assumed decay heat distribution would have negligible effect upon overall stress evaluations. In addition, maximum change in the corresponding temperatures for the three cases is less than 6°F, with the uniform decay heat distribution producing maximum temperature in the seal region.

Table 3-100. Case 1, Maximum Component Temperatures[a]

Component	Node_1	Node_2	Node	Max_Temp
Outside Shell	101	2894	606	1.8090E+02
Bottom Plate	3001	3232	3120	1.8160E+02
Lid	3233	3424	3233	1.8210E+02
Shell Cavity	4001	4998	4227	1.9420E+02
Plug	5001	5404	5001	1.9820E+02
Tungsten	6001	7656	7377	1.8620E+02
LAST-A-FOAM	8001	10791	9501	1.8160E+02

Table 3-101. Case 2, Maximum Component Temperatures[b]

Component	Node_1	Node_2	Node	Max_Temp
Outside Shell	101	2894	620	1.7830E+02
Bottom Plate	3001	3232	3120	1.7850E+02
Lid	3233	3424	3233	1.7680E+02
Shell Cavity	4001	4998	4482	1.8920E+02
Plug	5001	5404	5012	1.8000E+02
Tungsten	6001	7656	6392	1.8120E+02
LAST-A-FOAM	8001	10791	8197	1.7810E+02

Table 3-102. Case 3, Maximum Component Temperatures[c]

Component	Node_1	Node_2	Node	Max_Temp
Outside Shell	101	2894	634	1.8120E+02
Bottom Plate	3001	3232	3120	1.8060E+02
Lid	3233	3424	3233	1.8000E+02
Shell Cavity	4001	4998	4497	1.9310E+02
Plug	5001	5404	5012	1.8350E+02
Tungsten	6001	7656	6432	1.8450E+02
LAST-A-FOAM	8001	10791	8197	1.8030E+02

a. ***Case 1*** – *Decay heat uniformly distributed over the cask cavity cylindrical surface, top surface, and bottom surface (as in the AOS analyses).*

b. ***Case 2*** – *Decay heat distributed over the cask cavity cylindrical surface, top surface, and bottom surface, such that the cylindrical surface receives twice the heat intensity as the top and bottom surfaces.*

c. ***Case 3*** – *Decay heat distributed over only cask cavity cylindrical surface, with the top and bottom surfaces receiving no heat.*

Table 3-103. Case 1, Stress (psi/MPa)

Location	Sigma_1	Sigma_2	Sigma_3	Pm	Pb
1	1.0456E+02	-1.8983E+02	-2.8034E+01	2.9439E+02	4.2926E+02
	7.2091E-01	-1.3088E+00	-1.9329E-01	2.0297E+00	2.9597E+00
2	1.3149E+02	-2.9406E+02	-8.4539E+01	4.2555E+02	8.7203E+02
	9.0661E-01	-2.0275E+00	-5.8288E-01	2.9341E+00	6.0124E+00
3	1.0021E+02	-1.8730E+02	-2.2414E+01	2.8752E+02	4.2741E+02
	6.9094E-01	-1.2914E+00	-1.5454E-01	1.9823E+00	2.9469E+00
4	6.3127E+02	-2.1814E+03	-4.4076E+02	2.8126E+03	5.5355E+03
	4.3524E+00	-1.5040E+01	-3.0390E+00	1.9392E+01	3.8166E+01
5	6.2466E+02	-2.4329E+03	-9.8919E+02	3.0575E+03	4.8291E+03
	4.3069E+00	-1.6774E+01	-6.8202E+00	2.1081E+01	3.3295E+01
6	9.6377E+01	-1.2090E+03	-1.3048E+03	1.3054E+03	1.5833E+03
	6.6450E-01	-8.3357E+00	-8.9960E+00	9.0002E+00	1.0916E+01
7	-1.9217E+01	-4.1327E+02	2.4598E+01	3.9406E+02	4.2739E+02
	-1.3249E-01	-2.8494E+00	1.6960E-01	2.7169E+00	2.9468E+00
8	-1.9485E+01	-4.1288E+02	-1.5849E-01	3.9339E+02	4.2023E+02
	-1.3434E-01	-2.8467E+00	-1.0927E-03	2.7123E+00	2.8974E+00
9	-1.9384E+01	-4.1271E+02	-1.5390E+00	3.9333E+02	4.1618E+02
	-1.3364E-01	-2.8456E+00	-1.0611E-02	2.7119E+00	2.8695E+00
10	-7.2193E+01	-5.3770E+02	6.2101E+01	4.6550E+02	9.5760E+02
	-4.9775E-01	-3.7073E+00	4.2817E-01	3.2095E+00	6.6024E+00
11	-1.2200E+02	-6.7410E+02	-3.2254E+02	5.5211E+02	1.2549E+02
	-8.4114E-01	-4.6478E+00	-2.2238E+00	3.8066E+00	8.6522E-01
12	2.5799E+00	-8.1753E+02	-8.1351E+02	8.2011E+02	1.7232E+02
	1.7788E-02	-5.6367E+00	-5.6090E+00	5.6545E+00	1.1881E+00
13	-8.6733E+01	-1.2094E+03	-1.2100E+02	1.1227E+03	8.1844E+02
	-5.9800E-01	-8.3386E+00	-8.3430E-01	7.7406E+00	5.6430E+00
14	-6.9338E+01	-1.0534E+03	5.7286E+01	9.8411E+02	6.6719E+02
	-4.7807E-01	-7.2632E+00	3.9497E-01	6.7852E+00	4.6001E+00
15	2.1678E+02	-2.8099E+02	-3.4633E+01	4.9777E+02	8.3966E+02
	1.4946E+00	-1.9374E+00	-2.3879E-01	3.4320E+00	5.7893E+00
16	6.5964E+01	-1.3093E+02	-3.3301E+01	1.9689E+02	3.3071E+02
	4.5480E-01	-9.0271E-01	-2.2960E-01	1.3575E+00	2.2802E+00

17	3.0783E+01	-9.2873E+01	-1.1470E+01	1.2366E+02	2.1759E+02
	2.1224E-01	-6.4034E-01	-7.9082E-02	8.5258E-01	1.5002E+00
18	4.5328E+01	-9.9979E+01	5.5228E+02	1.4531E+02	6.1413E+01
	3.1252E-01	-6.8933E-01	3.8078E+00	1.0019E+00	4.2343E-01
19	-1.8918E+01	-2.1523E+02	6.9267E+02	1.9631E+02	2.1305E+02
	-1.3043E-01	-1.4840E+00	4.7758E+00	1.3535E+00	1.4689E+00
20	-3.7965E+01	-5.4220E+02	1.6813E+02	5.0423E+02	2.4979E+02
	-2.6176E-01	-3.7383E+00	1.1592E+00	3.4765E+00	1.7222E+00
21	3.1481E+00	-8.6388E+01	-8.2724E+01	8.9536E+01	1.2184E+02
	2.1705E-02	-5.9563E-01	-5.7036E-01	6.1733E-01	8.4008E-01
22	-2.8719E+01	-1.4109E+02	-1.3557E+02	1.1237E+02	1.3962E+02
	-1.9801E-01	-9.7277E-01	-9.3474E-01	7.7476E-01	9.6264E-01

Table 3-104. Case 2, Stress (psi/MPa)

Location	Sigma_1	Sigma_2	Sigma_3	Pm	Pb
1	1.0626E+02	-1.8898E+02	-1.7071E+01	2.9524E+02	4.2317E+02
	7.3263E-01	-1.3029E+00	-1.1770E-01	2.0356E+00	2.9176E+00
2	1.3586E+02	-3.0081E+02	-9.1768E+01	4.3667E+02	8.9696E+02
	9.3669E-01	-2.0740E+00	-6.3272E-01	3.0107E+00	6.1843E+00
3	1.0306E+02	-1.8881E+02	-1.6976E+01	2.9187E+02	4.2935E+02
	7.1056E-01	-1.3018E+00	-1.1704E-01	2.0124E+00	2.9603E+00
4	6.8554E+02	-2.0418E+03	-4.0530E+02	2.7273E+03	5.3361E+03
	4.7267E+00	-1.4077E+01	-2.7944E+00	1.8804E+01	3.6791E+01
5	7.1795E+02	-2.3302E+03	-7.5061E+02	3.0481E+03	4.8219E+03
	4.9501E+00	-1.6066E+01	-5.1752E+00	2.1016E+01	3.3246E+01
6	1.0763E+02	-1.1763E+03	-9.7713E+02	1.2839E+03	1.6656E+03
	7.4210E-01	-8.1103E+00	-6.7371E+00	8.8524E+00	1.1484E+01
7	-2.0446E+01	-4.0750E+02	2.8551E+01	3.8706E+02	4.7858E+02
	-1.4097E-01	-2.8096E+00	1.9685E-01	2.6687E+00	3.2997E+00
8	-2.0978E+01	-4.0600E+02	-4.8058E-01	3.8502E+02	4.5443E+02
	-1.4464E-01	-2.7992E+00	-3.3135E-03	2.6546E+00	3.1332E+00
9	-2.0912E+01	-4.0664E+02	9.9173E+00	3.8573E+02	4.6822E+02
	-1.4418E-01	-2.8037E+00	6.8378E-02	2.6595E+00	3.2283E+00
10	-5.2623E+01	-4.2684E+02	-1.1668E+02	3.7421E+02	5.2219E+02
	-3.6282E-01	-2.9429E+00	-8.0447E-01	2.5801E+00	3.6003E+00
11	-4.6965E+01	-4.3616E+02	-2.8320E+02	3.8919E+02	1.9263E+01
	-3.2381E-01	-3.0072E+00	-1.9526E+00	2.6834E+00	1.3281E-01
12	1.4280E+00	-4.9718E+02	-4.9572E+02	4.9861E+02	7.6981E+00
	9.8457E-03	-3.4279E+00	-3.4179E+00	3.4378E+00	5.3076E-02
13	-6.2872E+01	-1.0239E+03	-1.9446E+02	9.6098E+02	8.5804E+02
	-4.3349E-01	-7.0592E+00	-1.3407E+00	6.6258E+00	5.9160E+00
14	-3.7412E+01	-8.9557E+02	-3.3335E+01	8.5816E+02	6.0010E+02
	-2.5795E-01	-6.1747E+00	-2.2984E-01	5.9168E+00	4.1376E+00
15	2.1957E+02	-2.7300E+02	-2.5945E+01	4.9258E+02	8.3463E+02
	1.5139E+00	-1.8823E+00	-1.7889E-01	3.3962E+00	5.7545E+00
16	6.4300E+01	-1.2668E+02	-3.6108E+01	1.9097E+02	3.1495E+02
	4.4333E-01	-8.7340E-01	-2.4895E-01	1.3167E+00	2.1715E+00

17	2.8317E+01	-8.6767E+01	1.9932E+00	1.1508E+02	2.0063E+02
	1.9524E-01	-5.9824E-01	1.3742E-02	7.9347E-01	1.3833E+00
18	7.6299E+00	-4.6973E+01	1.0789E+02	5.4603E+01	6.5954E+01
	5.2606E-02	-3.2387E-01	7.4391E-01	3.7647E-01	4.5473E-01
19	1.4607E+01	-8.9408E+01	8.3077E+01	1.0401E+02	1.6972E+02
	1.0071E-01	-6.1645E-01	5.7280E-01	7.1716E-01	1.1702E+00
20	2.8480E+00	-1.0012E+02	-6.3027E+01	1.0297E+02	1.9318E+02
	1.9636E-02	-6.9030E-01	-4.3456E-01	7.0994E-01	1.3319E+00
21	5.8399E+00	-7.5225E+01	-6.8959E+01	8.1065E+01	1.2310E+02
	4.0265E-02	-5.1866E-01	-4.7546E-01	5.5892E-01	8.4872E-01
22	-2.2860E+01	-5.5165E+01	-4.5433E+01	3.2305E+01	5.0119E+01
	-1.5761E-01	-3.8035E-01	-3.1325E-01	2.2273E-01	3.4556E-01

Table 3-105. Case 3, Stress (psi/MPa)

Location	Sigma_1	Sigma_2	Sigma_3	Pm	Pb
1	1.1332E+02	-2.0167E+02	-1.7830E+01	3.1499E+02	4.5244E+02
	7.8130E-01	-1.3904E+00	-1.2294E-01	2.1717E+00	3.1195E+00
2	1.4456E+02	-3.1945E+02	-9.9536E+01	4.6401E+02	9.5345E+02
	9.9670E-01	-2.2025E+00	-6.8628E-01	3.1992E+00	6.5738E+00
3	1.0883E+02	-1.9587E+02	-1.1934E+01	3.0470E+02	4.4224E+02
	7.5036E-01	-1.3504E+00	-8.2283E-02	2.1008E+00	3.0492E+00
4	6.9648E+02	-2.1058E+03	-4.1724E+02	2.8022E+03	5.4835E+03
	4.8021E+00	-1.4519E+01	-2.8768E+00	1.9321E+01	3.7807E+01
5	7.3302E+02	-2.4089E+03	-7.8913E+02	3.1419E+03	4.9727E+03
	5.0540E+00	-1.6609E+01	-5.4409E+00	2.1663E+01	3.4285E+01
6	1.1040E+02	-1.2142E+03	-1.0213E+03	1.3246E+03	1.7067E+03
	7.6121E-01	-8.3716E+00	-7.0419E+00	9.1328E+00	1.1767E+01
7	-2.1151E+01	-4.2187E+02	3.0050E+01	4.0072E+02	5.1802E+02
	-1.4583E-01	-2.9087E+00	2.0719E-01	2.7629E+00	3.5716E+00
8	-2.2697E+01	-4.1929E+02	-8.1965E-01	3.9660E+02	4.9239E+02
	-1.5649E-01	-2.8909E+00	-5.6513E-03	2.7344E+00	3.3949E+00
9	-2.0069E+01	-4.2351E+02	2.3821E+01	4.0344E+02	5.2751E+02
	-1.3837E-01	-2.9200E+00	1.6424E-01	2.7816E+00	3.6370E+00
10	1.0335E+02	-4.4853E+02	-3.3947E+02	5.5188E+02	1.1988E+00
	7.1255E-01	-3.0925E+00	-2.3405E+00	3.8050E+00	8.2654E-03
11	1.0720E+02	-2.2665E+02	-2.4470E+02	3.3385E+02	1.8718E+02
	7.3910E-01	-1.5627E+00	-1.6871E+00	2.3018E+00	1.2906E+00
12	1.2235E+01	-1.3838E+02	-1.2779E+02	1.5061E+02	2.1751E+02
	8.4356E-02	-9.5409E-01	-8.8110E-01	1.0384E+00	1.4996E+00
13	3.8109E+00	-8.7929E+02	-2.9444E+02	8.8310E+02	9.4655E+02
	2.6275E-02	-6.0625E+00	-2.0301E+00	6.0887E+00	6.5262E+00
14	1.4413E+01	-7.5512E+02	-1.5131E+02	7.6954E+02	5.5921E+02
	9.9376E-02	-5.2064E+00	-1.0432E+00	5.3058E+00	3.8556E+00
15	2.3622E+02	-2.9365E+02	-2.7933E+01	5.2987E+02	8.9787E+02
	1.6287E+00	-2.0246E+00	-1.9259E-01	3.6533E+00	6.1906E+00
16	6.9144E+01	-1.3625E+02	-3.8755E+01	2.0539E+02	3.3867E+02
	4.7673E-01	-9.3939E-01	-2.6721E-01	1.4161E+00	2.3350E+00

17	3.0430E+01	-9.3259E+01	2.3069E+00	1.2369E+02	2.1560E+02
	2.0981E-01	-6.4300E-01	1.5906E-02	8.5281E-01	1.4865E+00
18	8.1408E+00	-5.0305E+01	1.1570E+02	5.8446E+01	7.0571E+01
	5.6129E-02	-3.4684E-01	7.9773E-01	4.0297E-01	4.8657E-01
19	1.5492E+01	-9.5652E+01	8.9411E+01	1.1114E+02	1.8136E+02
	1.0681E-01	-6.5950E-01	6.1647E-01	7.6631E-01	1.2505E+00
20	2.8083E+00	-1.0699E+02	-6.7307E+01	1.0980E+02	2.0545E+02
	1.9362E-02	-7.3769E-01	-4.6406E-01	7.5706E-01	1.4165E+00
21	1.1268E+01	-6.6794E+01	-5.5199E+01	7.8062E+01	1.3120E+02
	7.7691E-02	-4.6053E-01	-3.8058E-01	5.3822E-01	9.0459E-01
22	-2.4790E+01	-5.9183E+01	-4.8922E+01	3.4393E+01	5.6968E+01
	-1.7092E-01	-4.0805E-01	-3.3730E-01	2.3713E-01	3.9278E-01

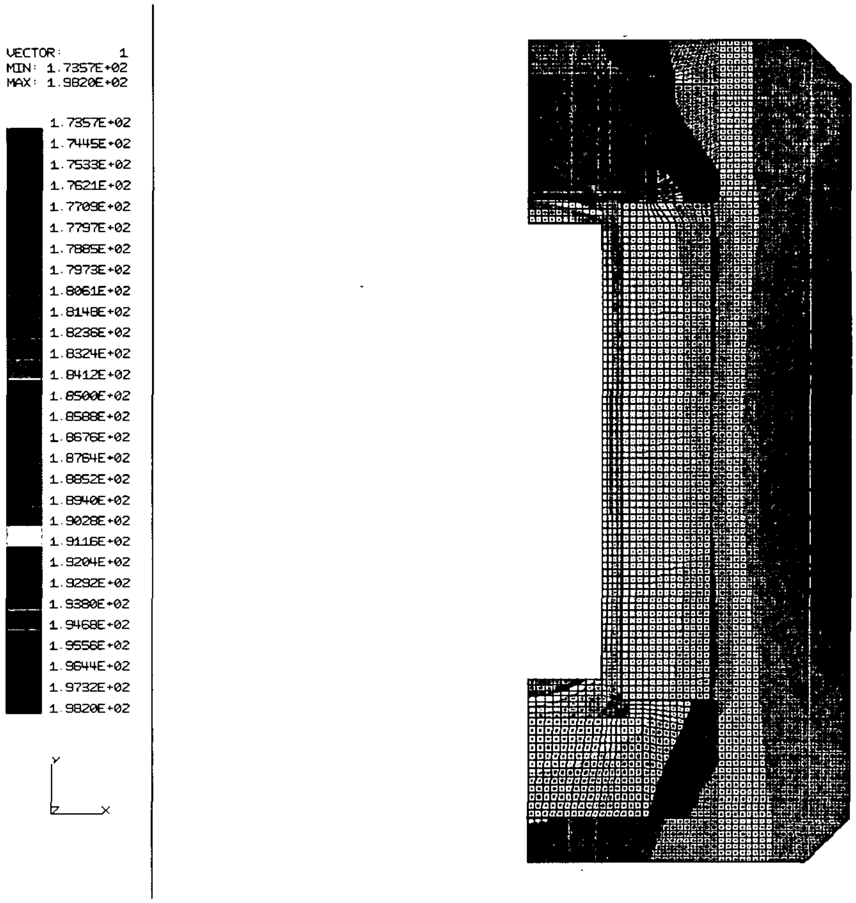

Figure 3-146. Case 1 – Temperature

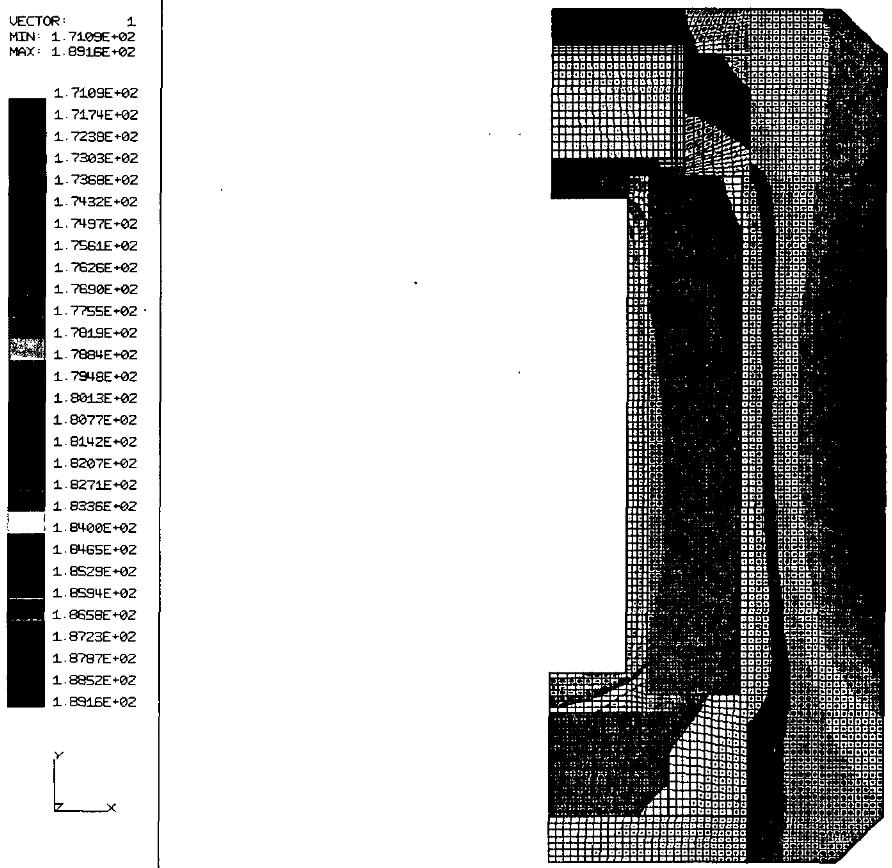

Figure 3-147. Case 2 – Temperature

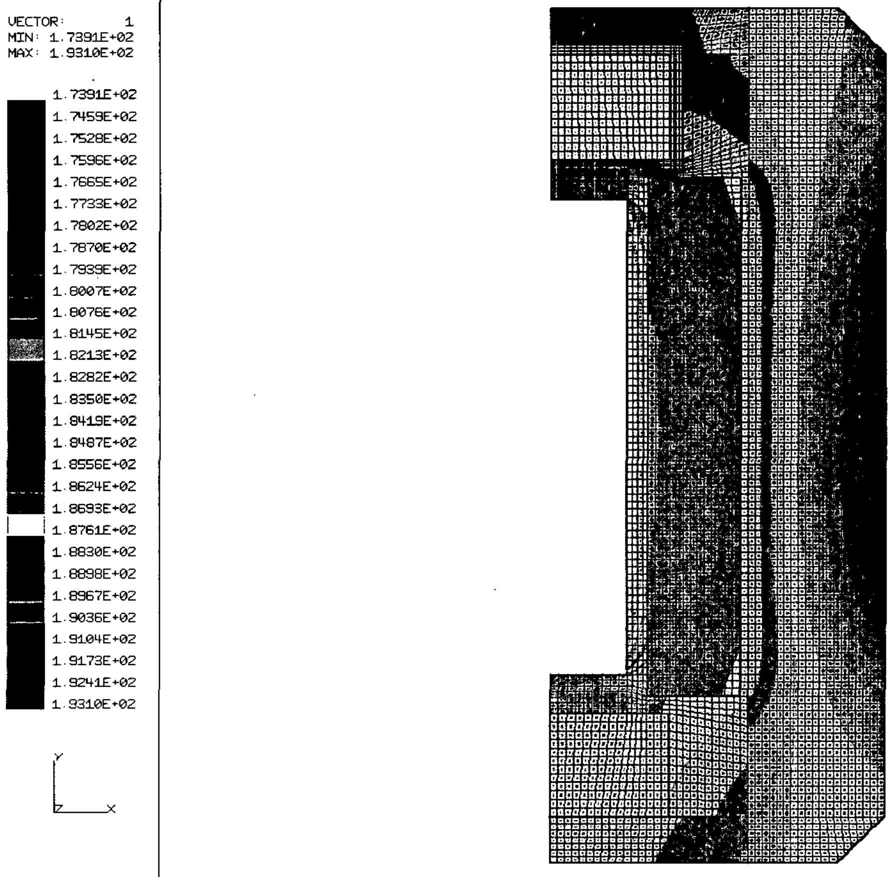

Figure 3-148. Case 3 – Temperature

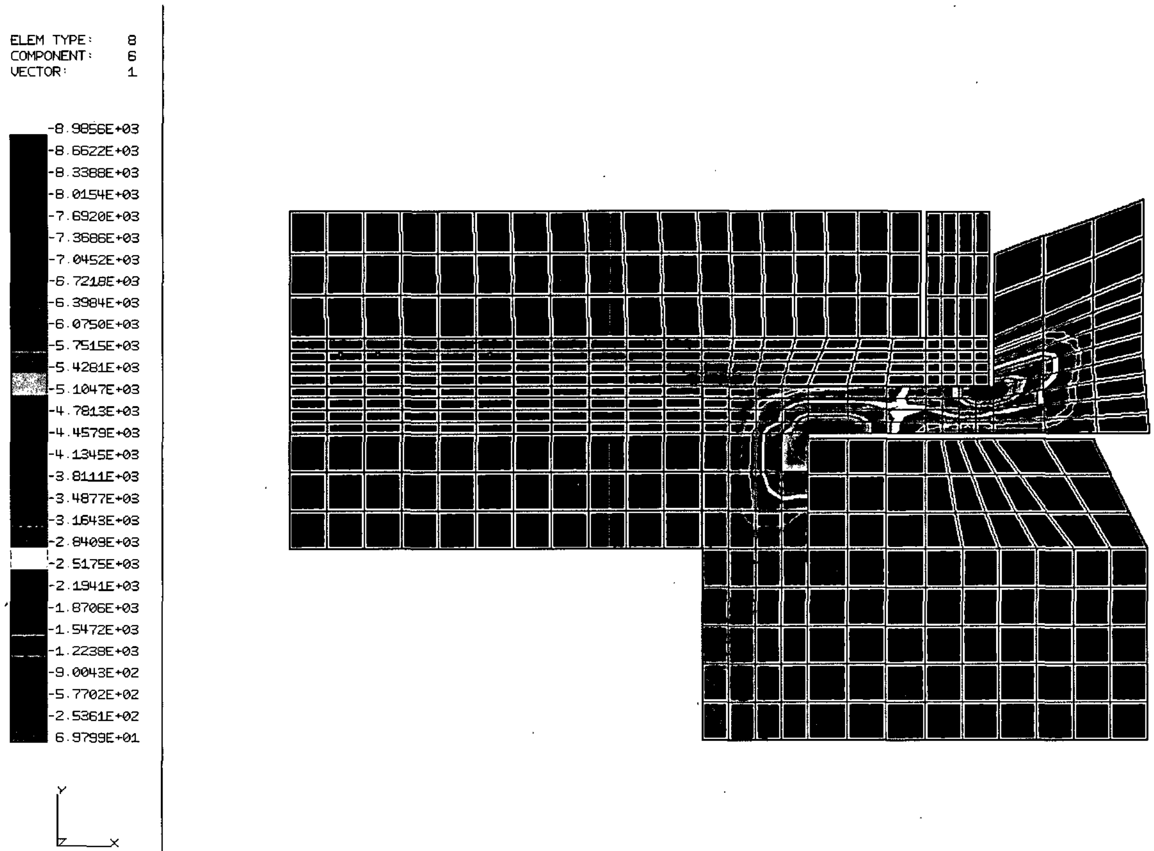

Figure 3-149. Case 1 – Maximum Principal Stress at Lid Corner

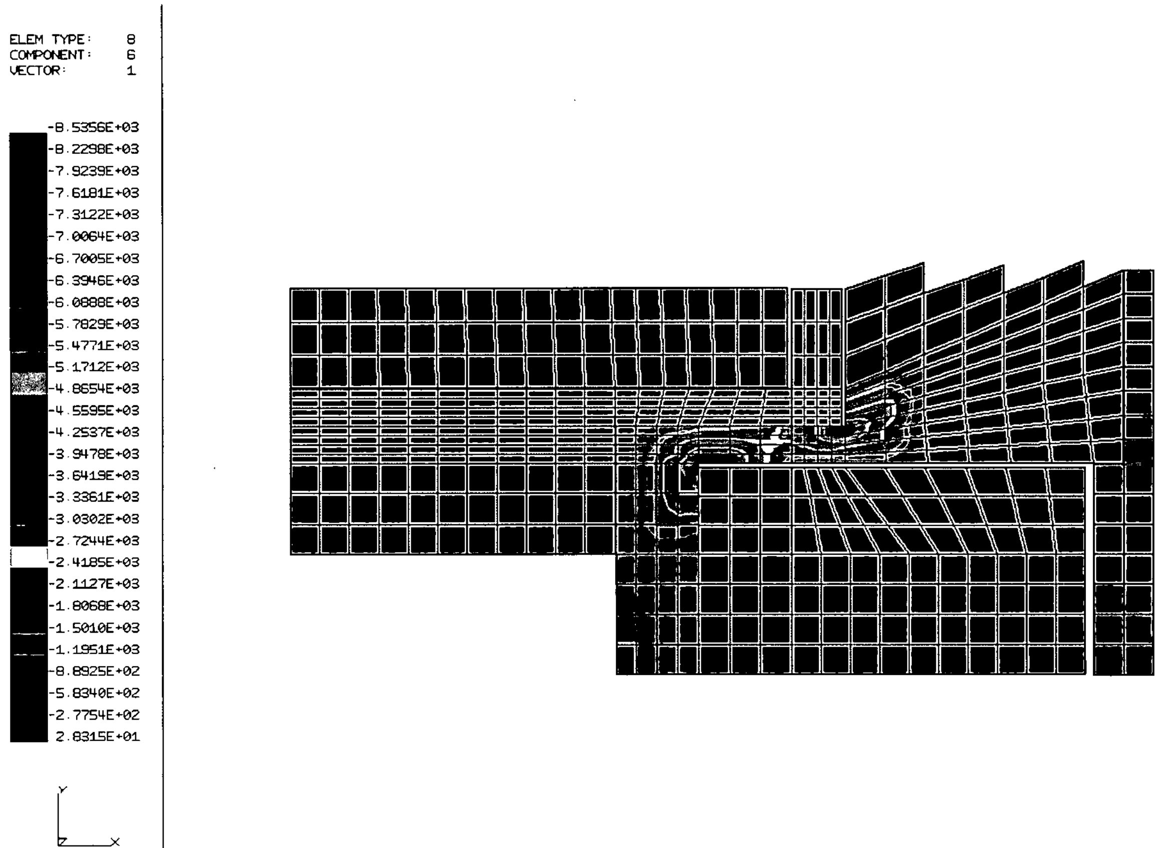

Figure 3-150. Case 2 – Maximum Principal Stress at Lid Corner

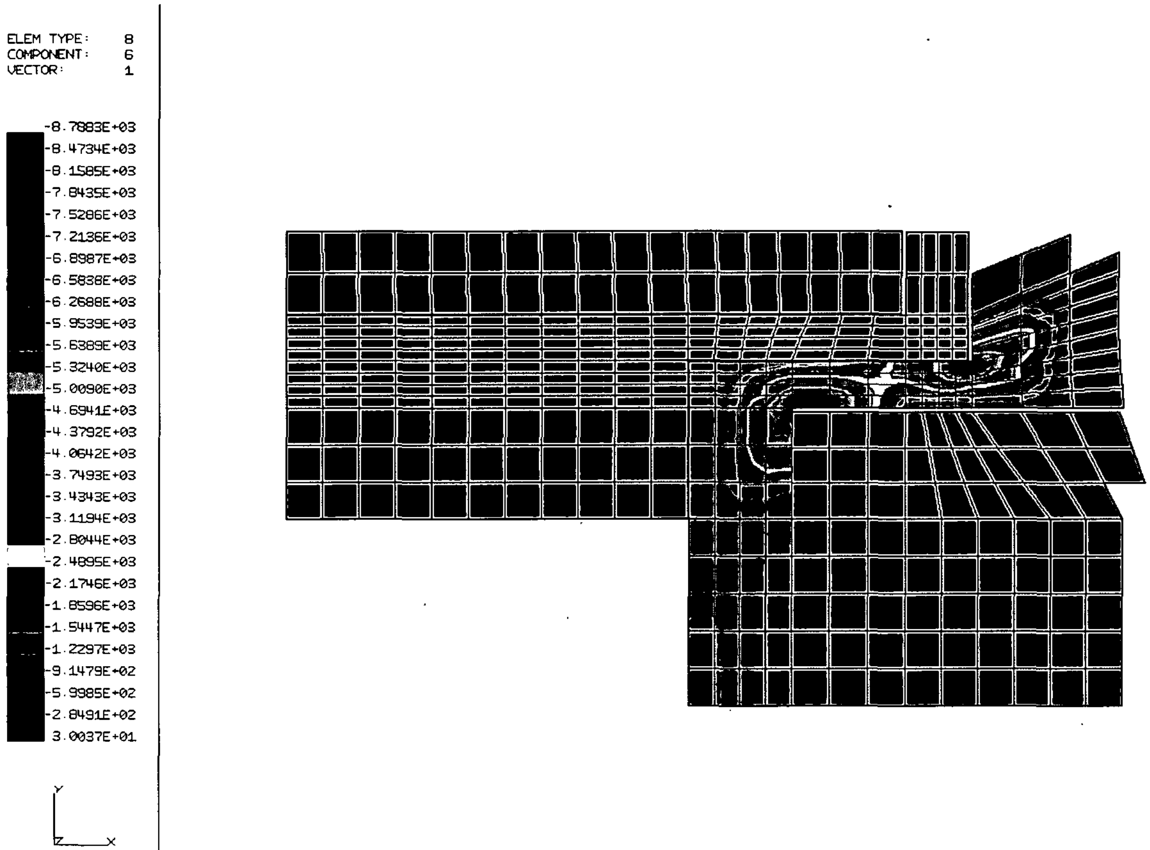

Figure 3-151. Case 3 – Maximum Principal Stress at Lid Corner

3.5.10 Justification for Use of LAST-A-FOAM 3700 Thermal Properties

The values used in the SAR analyses were taken from General Plastics Manufacturing Company data sheet for LAST-A-FOAM FR-3700. The latest thermal conduction data published by General Plastics differs from the data available when the SAR was prepared. Both are presented in Table 3-106.

Table 3-106. LAST-A-FOAM FR-3700 – Differences between SAR and Product's Current Values

Product	Old K Value (Btu/hr-ft^2/°F)	New K Value (Btu/hr-ft^2/°F)
FR-3710	0.279	0.213
FR-3718	0.356	0.324
FR-3720	0.376	0.349

The largest change is in FR-3710, where the new value is 76% of the old value. FR-3710 is the product used in the Model AOS-050 transport package. The effect of the change in conductivity is evaluated by recalculating temperatures and thermal stress in the Model AOS-050, using thermal conductivity values reduced by a 0.75 factor, and comparing the resulting margins of safety and maximum component temperatures to the SAR values.

Table 3-107 and Table 3-108 list the Model AOS-050 margins of safety for Normal conditions of transport. Table 3-107 presents values corresponding to the reduced K, while Table 3-108 contains the values provided in the SAR. A comparison of these two tables shows that the reduced K values produce no change in margins of safety for normal conditions.

Table 3-109 and Table 3-110 list the Model AOS-050 margins of safety for Hypothetical Accident conditions of transport. Table 3-109 presents values corresponding to the reduced K, while Table 3-110 contains the values provided in the SAR. A comparison of these two tables shows that the reduced K values produce small changes in margins of safety for accident conditions where margins of safety are high, but no change where accident margins of safety are less than 1.0.

Finally, Table 3-111 and Table 3-112 list the Model AOS-050 maximum component temperatures for the fire accident condition. Table 3-111 presents values corresponding to the reduced K, while Table 3-112 contains the values provided in the SAR. A comparison of these two tables shows that the reduced K values produce small changes in maximum component temperature. The maximum temperature change is a 16°F reduction in foam temperature, from 563°F to 547°F. Other maximum component temperatures increase by less than 3°F.

Table 3-107. Reduced K Min MS for Normal Conditions of Transport

Ld_Cmb	Load_Cases					Min_MS	Loc	Str_Cmb
101	102	201	211	0	0	5.819E+00	4	Pm+Pb
102	104	201	211	0	0	2.164E+00	5	Pm+Pb+Q
103	103	201	211	0	0	2.686E+00	5	Pm+Pb+Q
104	101	201	202	211	0	5.535E+00	4	Pm+Pb
105	105	201	202	211	0	5.535E+00	4	Pm+Pb
106	101	201	203	211	0	4.918E+00	4	Pm+Pb
107	105	201	203	211	0	4.918E+00	4	Pm+Pb
215	215	101	201	211	0	5.145E+00	4	Pm+Pb
216	216	101	201	211	0	1.285E+00	15	Pm
217	216	104	201	211	0	1.285E+00	15	Pm
221	221	101	201	211	0	5.812E+00	4	Pm+Pb
222	222	101	201	211	0	5.607E+00	4	Pm+Pb
223	223	101	201	211	0	5.408E+00	4	Pm+Pb
231	231	102	201	211	0	3.034E+00	4	Pm+Pb
232	232	102	201	211	0	1.032E+00	4	Pm+Pb

Table 3-108. SAR Min MS for Normal Conditions of Transport

Ld_Cmb	Load_Cases					Min_MS	Loc	Str_Cmb
101	102	201	211	0	0	5.819E+00	4	Pm+Pb
102	104	201	211	0	0	2.164E+00	5	Pm+Pb+Q
103	103	201	211	0	0	2.686E+00	5	Pm+Pb+Q
104	101	201	202	211	0	5.535E+00	4	Pm+Pb
105	105	201	202	211	0	5.535E+00	4	Pm+Pb
106	101	201	203	211	0	4.918E+00	4	Pm+Pb
107	105	201	203	211	0	4.918E+00	4	Pm+Pb
215	215	101	201	211	0	5.145E+00	4	Pm+Pb
216	216	101	201	211	0	1.285E+00	15	Pm
217	216	104	201	211	0	1.285E+00	15	Pm
221	221	101	201	211	0	5.812E+00	4	Pm+Pb
222	222	101	201	211	0	5.607E+00	4	Pm+Pb
223	223	101	201	211	0	5.408E+00	4	Pm+Pb
231	231	102	201	211	0	3.034E+00	4	Pm+Pb
232	232	102	201	211	0	1.032E+00	4	Pm+Pb

Table 3-109. Reduced K Min MS for Hypothetical Accident Conditions of Transport

Ld_Cmb	Load_Cases					Min_MS	Loc	Str_Cmb
301	301	102	201	211	0	3.491E+00	4	Pm+Pb
302	302	102	201	211	0	8.885E+00	4	Pm+Pb
303	303	102	201	211	0	3.318E+00	1	Pm
304	304	105	202	211	0	2.818E+00	4	Pm+Pb
305	305	105	202	211	0	7.495E+00	1	Pm+Pb
306	306	105	202	211	0	2.537E+00	1	Pm
310	204	101	211	0	0	3.028E+00	4	Pm+Pb
311	311	101	201	211	0	5.885E-01	15	Pm
312	311	104	201	211	0	5.885E-01	15	Pm
350	111	201	211	0	0	1.305E+01	4	Pm+Pb
351	112	201	211	0	0	1.305E+01	4	Pm+Pb
352	113	201	211	0	0	1.305E+01	4	Pm+Pb
353	114	201	211	0	0	1.305E+01	4	Pm+Pb
354	115	201	211	0	0	1.305E+01	4	Pm+Pb
355	116	201	211	0	0	1.305E+01	4	Pm+Pb

Table 3-110. SAR Min MS for Hypothetical Accident Conditions of Transport

Ld_Cmb	Load_Cases					Min_MS	Loc	Str_Cmb
301	301	102	201	211	0	3.741E+00	4	Pm+Pb
302	302	102	201	211	0	9.436E+00	4	Pm+Pb
303	303	102	201	211	0	3.466E+00	1	Pm
304	304	105	202	211	0	2.818E+00	4	Pm+Pb
305	305	105	202	211	0	7.495E+00	1	Pm+Pb
306	306	105	202	211	0	2.537E+00	1	Pm
310	204	101	211	0	0	3.028E+00	4	Pm+Pb
311	311	101	201	211	0	5.885E-01	15	Pm
312	311	104	201	211	0	5.885E-01	15	Pm
350	111	201	211	0	0	1.491E+01	4	Pm+Pb
351	112	201	211	0	0	1.491E+01	4	Pm+Pb
352	113	201	211	0	0	1.491E+01	4	Pm+Pb
353	114	201	211	0	0	1.491E+01	4	Pm+Pb
354	115	201	211	0	0	1.491E+01	4	Pm+Pb
355	116	201	211	0	0	1.491E+01	4	Pm+Pb

Table 3-111. Reduced K Fire Condition Maximum Component Temperatures

Component	Node_1	Node_2	Node	Max_Temp
Outside Shell	101	2894	1107	4.2400E+02
Bottom Plate	3001	3232	3120	3.9480E+02
Lid	3233	3424	3233	3.9330E+02
Shell Cavity	4001	4998	4527	4.2570E+02
Plug	5001	5404	5001	4.0310E+02
Tungsten	6001	7656	6436	4.2210E+02
LAST-A-FOAM	8001	10791	10035	5.4670E+02

Table 3-112. SAR Fire Condition Maximum Component Temperatures

Component	Node_1	Node_2	Node	Max_Temp
Outside Shell	101	2894	1117	4.2140E+02
Bottom Plate	3001	3232	3120	3.9210E+02
Lid	3233	3424	3233	3.9160E+02
Shell Cavity	4001	4998	4522	4.2290E+02
Plug	5001	5404	5001	4.0080E+02
Tungsten	6001	7656	6440	4.1940E+02
LAST-A-FOAM	8001	10791	10034	5.6270E+02

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